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JOINT SCIENTIFIC MEETING LISBON 2025

# IAGA / IASPEI Joint Scientific Meeting

31 August - 5 September 2025
Lisbon, Portugal

# BOOK OF ABSTRACTS

IUGG | IAGA International Association of Geomagnetism and Aeronomy

IUGG | IASPEI International Association of Seismology and Physics of the Earth's Interior

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# Abstracts

## A01/A02 Paleomagnetism, Rock and Environmental Magnetism, and applications in Earth and Planetary Processes

### AS25-0064

# Does the vertical distribution of magnetic susceptibility of topsoils represent a given site?

*Eduard Petrovsky[1], Tadeusz Magiera[2], Michal Jankowski[3], Hana Grison[1], Marcin Szuszkiewicz[2], Michal Bucko[2], Marcin Sykula[3], Sarka Stejskalova[1], Malgorza Wawer[2], Jaroslaw Zawadzki[4], Piotr Fabijanczyk[4]*

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Vertical distribution of magnetic susceptibility of soils is often used to assess the origin of values measured on the surface and to discriminate the natural and anthropogenic contributions. Assuming the efficient penetration (response) depth of about 10 cm of the most often used Bartington instrument, vertical distribution measured on cores 30–40 cm long is supposed to reveal magnetic enhancement due to atmospherically deposited dust, or gradual increase with depth caused by weathering of iron-rich basement rocks. However, due to the heterogeneity of soils, the design of the field measurements in terms of the number and distribution of measured vertical profiles plays crucial role. In our contribution we will discuss the problem of spatial variability of topsoil vertical profiles of magnetic susceptibility in ochre soils (WRB 2022: Tsitelic Cambisols Arenic), developed on Quaternary glaciofluvial sandy deposits (the Toruń Basin, northern Poland). The measured profiles were distributed within a regular grid along a rectangular perimeter with sides 5 and 10 m from the central reference point. Our observations suggest that increasing the number of vertical profiles does not reduce significantly the spatial variability of data related to individual depths (expressed in terms of standard deviation, which is rather high). However, while the interpretation of individual vertical profiles still depends on the researcher's experience, the average profile provides a more reliable representation of magnetic enhancement caused by natural (lithogenic/pedogenic) and/or anthropogenic contributions. Hence, we recommend adjusting the number of profiles and the sampling density based on the local variability of soil parameters.

## AS25-0094

# Mechanism for the formation of the Jurassic Large Granite Province in SE China insight from magnetic fabric measurement, paleomagnetic investigation

*Hongsheng Liu[1], Yan Chen[2], Bo Wang[3], Michel Faure[4], Brunon Scaillet[5], Fangfang Huang[6], Rucheng Wang[7]*

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The coupling between the tectonics and magmatism, especially for those regions with enormous volume of magmatism, i.e., the Large Granite Provinces (LGPs), is recorded during emplacement of plutons and can be used as one powerful tool to infer the magma system evolution. The Jurassic LGPs developed in the SE part of the South China Block (SCB) is characterized by widespread felsic plutons in a surface of 1500 km long and 800 km wide.

Integrating field observation, magnetic fabric measurement, paleomagnetic investigation and gravity modelling, we propose that the Jurassic LGPs in South China is derived from the partial melting of the thickened lower continental crust produced by the Triassic continental subduction of the SCB under its neighbouring blocks. Due to the relatively low rigidity of the SE part of the SCB with respect to its NW part, the Triassic deformation was essentially absorbed by its SE part and its crust was consequently thickened. The scarcity of Jurassic sedimentation within the SE part of SCB with respect to its surrounding areas suggests that this SE part of SCB was not only thickened but also formed a plateau-shape topography. This makes the increases of both pressure and temperature in the lower crust which permits partial melting of the lower continental crust of the SE part of the SCB during the long decompression processes.

We concluded that the pre-magmatic tectonic events and nature of the crust are important for the evolution of the Jurassic magmatism in the SE part of the SCB.

## AS25-0168

# Determining paleo-stress signals using rock magnetism

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Stress and shock effects have been experienced through impacts and seismic activities, since the formation of the Earth. From tectonic processes to impact cratering the crust undergoes stress fields from $10^2$ to $10^6$ MPa, which can have a colossal effect on rock magnetic signals. For the past 70 years shock remanent magnetisation has primarily been studied at pressures >> 1 GPa. From explosive tests to hypervelocity experiments, magnetisation and demagnetisation effects have been observed with respect to distance and intensity. Attention has always been drawn to high-pressure stress effects because our current understanding of stress effects on magnetic recordings is based on single domain (SD) theory. It is believed that SD grains are the most reliable and stable magnetic recorders over the geological timescale. However, most recent models have shown that single—vortex (SV) grains retain most stable magnetisation with only 0.1 GPa of stress. Changes in magnitude and anisotropy of magnetic susceptibility in response to high stresses within the elastic, inelastic and plastically deformed rocks have also been found. Although anisotropy of magnetic susceptibility (AMS) has always primarily been used as a tool to determine direction of volcanic and sedimentary flows. In this talk, we highlight low stress effects within the elastic regime of basalts on the AMS under different experimental configurations. We show that the AMS may have further purpose than reflecting the alignment of the underlying petrofabric and how this can be used to determine palaeo-stress signals to help our understanding of processes in structural geology.

## AS25-0172

# Magnetic and petrological signature of a plagioclase ultraphyric basalt in Westfjords, Iceland—implications for origin and emplacement

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The Westfjords of Iceland host flood basalt sequences featuring Plagioclase Ultraphyric Basalts (PUBs)—basaltic rocks with >25% crystal content dominated by anorthitic plagioclase with minor olivine and clinopyroxene. This study investigates their magmatic origin and flow dynamics through integrated analyses. The examined PUBs contain up to 66% plagioclase—the highest reported value for these formations. Thermobarometric calculations indicate magma equilibration at mid-crustal depths (11.6±2.5 km) and temperatures of 1204±10 °C. Plagioclase and olivine macrocryst cores (An85-89, Fo83-86) originated from a crystal mush, while their rims (An50-70, Fo48-84) crystallized from the carrier magma. The plagioclase trace elements composition shows equilibrium with their host magma, indicating localized magmatic processes rather than exotic sources. Despite high crystal content, field evidence indicates these flows behaved like typical basaltic lavas. This contradiction may be explained by crystal alignment reducing viscosity, thermal exchange maintaining lower melt viscosities, and shear thinning behavior. Anisotropy of Magnetic Susceptibility analysis along the K1, K2, and K3 axes reveals predominantly SE oriented flow directions, consistent with the Arnarfjörður central volcano source. The AMS measurements show strain patterns associated with very fluid lava flows. These patterns, combined with observed pepperitic structures at flow bases, suggest that the high crystal content modified both flow rheology and thermal properties.

This multidisciplinary approach and the AMS data revealing distinct strain patterns not previously documented in PUB studies, contributes to refined models of magma dynamics. The results highlight the importance of considering more complex emplacement mechanisms when studying crystal-rich magmas that appear to defy traditional rheological models.

## AS25-0217

# Magnetic studies of disturbed by the war soils in Ukraine

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The war in Ukraine has led to significant losses of fertile soil. Both agriculture and urbanized areas along the military contact line as well as missiles and drones' attacks have experienced substantial anthropogenic effects. The significant challenges are related to the soil loss in agrarian regions, pollution with heavy metals (HM) and other organic and non-organic components, and finally searching for the optimal methods of demining. The magnetic method is valuable tool for quantification of soil pollution with military-related heave metal emissions. Previously, soil magnetic measurements demonstrated high efficiency as a proxy for HMs pollution identification from industrial sources (Petrovský et al., 2013; Jordanova et al., 2021; Menshov et al., 2023; Magiera et al., 2025). In our study, the magnetic measurements have been conducted at the areas of former battlefields and missile strike zones in the Kyiv, Kharkiv, and Mykolaiv regions. These sites affected by military actions undergo significant transformations in both landscape structure and chemical composition. The chemical elements As, Ba, Cu, Fe, Pb, Zn have a positive correlation with magnetic susceptibility ($\chi$) on the unexploded ordnance (UXO) destruction site and on the middle caliber artillery shelled. The results of studies of the content of heavy metals in soil samples collected from different zones of the caponier (location of armored vehicles) demonstrated varying levels of contamination depending on the type of impurities and the chemical composition of the soil. The biggest impact is related to the unknown silver metallic color pollution, and slight effect is from the oil contamination.

## AS25-0350

# Isolating magnetosomal greigite as the source of an inverse magnetic fabric at IODP Site M0061 (Baltic Sea)

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Palaeomagnetic subsamples collected from IODP site M0061 lost up to 90% of bulk magnetic susceptibility (MS) during cold-room storage of 4 months, attributable to the alteration of single-domain magnetosomal greigite (Fe3S4). We resampled M0061 and took palaeomagnetic subsamples from three parallel Kullenberg piston cores. After measuring the natural remanent magnetization we made successive measurements of anisotropy of MS (AMS) over a period of 1 year in a controlled cool-room, keeping the subsamples humidified and exposed to air. Even though the subsamples had a normal oblate AMS fabric, which is expected for horizontally bedded sediments, we also observed a negative trend between the degree of anisotropy (Pj) and MS. In agreement with the previous result, MS decreased substantially over one year. We applied an AMS tensor subtraction routine to isolate the fabric of the decayed component and found an inverse fabric with low Pj. We conclude that the original AMS ellipsoid was determined by a mixture of a typical normal, oblate sedimentary fabric and a prolate, inverse magnetosomal fabric. The inverse orientation of the isolated fabric indicates that the long axis of the single-domain magnetosomal greigite (perhaps in chains) was perpendicular to the bedding plane, which implies that the magnetosomal greigite was deposited from the water column and contributes to a depositional remanent magnetisation (DRM). Our results show that greigite magnetofossils can (i) explain the presence of inverse AMS fabrics that have been reported in similar sedimentary environments and (ii) carry a DRM with a median destructive force of ~20 mT.

## AS25-0391

# LAPOD 2.0: Latin American Paleomagnetic Online Database, an advanced platform for data visualization, analysis, and paleomagnetic modeling in Latin America

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We introduce LAPOD 2.0, the latest update to the Latin American Online Paleomagnetic Database (LAPOD), a platform for accessing, analyzing, and visualizing paleomagnetic data across Latin America. LAPOD provides over 2,000 validated records from Mexico, the southwestern United States, Central America, and South America, ensuring high reliability through geolocation and age verification.

This update introduces advanced visualization tools that enhance data accessibility and interpretation. Users can now explore datasets spatially through an interactive georeferenced map, improving regional-scale analysis. Directional data can be plotted on stereo net, facilitating the study of secular variation, geomagnetic excursions, and directional trends. The improved time-series visualization enables a more fluid representation of records with calendar ages, facilitating the reconstruction of regional and global paleosecular variation curves. Additionally, expanded datasets now include magnetic properties experiments, such as susceptibility, hysteresis, and thermomagnetic curves, providing a comprehensive framework for paleomagnetic research and geomagnetic field modeling, as well as developing global and regional paleosecular variation curves.

LAPOD is a valuable resource for modeling the Earth's magnetic field, supporting global and regional paleosecular variation models to better understand the spatiotemporal behavior of geomagnetic variations. Additionally, this initiative aims to establish collaborative networks and funding partnerships to ensure continuous platform maintenance and updates.

By integrating these new features, LAPOD 2.0 strengthens its role as a community-driven and evolving resource, fostering interdisciplinary research and advancing the understanding of the Earth's magnetic history.

To explore LAPOD 2.0, visit: https://paleomagnetismo.org/pmagdb/.

## AS25-0490

# The laboratory CatVTM magnetometer: a valuable tool for constraining magnetic modeling in volcanic geothermal environments?

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The hydrothermal system at Krafla Volcano is home to one largest geothermal power plant in Iceland (Ármannsson et al., Jökull, 1987). This area has been studied with multiple geophysical methods such as electrical resistivity, electromagnetic, gravimetric and magnetic methods (Oliva-Urcia et al., GJI, 2011; Rosenkjaer et al., Geothermics, 2015; Scott et al., GRC Transactions, 2018). The general idea is to couple the different approaches to best localize the zones where geothermal fluids are circulating at depth. A good knowledge of the evolution with depth of the rock magnetization within the volcanic edifice could help to effectively solve the geophysical inverse problem from the aeromagnetic surveys.

Here, we employ laboratory measurements to assess the remanent magnetization at a temperature corresponding to that measured directly in the borehole, while also applying a controlled magnetic field to evaluate the induced magnetization due to the Earth's magnetic field at Krafla. To this end, we used the vibrating thermo-magnetometer developed in Montpellier (Poidras et al., EPS, 2009).

The results reveal that the difference in magnetization between fresh rocks and those affected by hydrothermal fluids is related to intensity rather than to direction of magnetization. In addition, we detected a geomagnetic excursion at 355.8 meters in KH-6, which could be the same than the one already detected at 293.2 m in borehole KH-3 (Oliva-Urcia et al., GJI, 2011). At this depth, it is conceivable that this is the Laschamp excursion dated at 42 Kyr.

## AS25-0530

# Deciphering magnetic Records in northern swedish estuarine Sediments: Evidence for greigite Formation

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The authigenic formation of greigite ($Fe_3S_4$) occurs during sediment diagenesis, and understanding its formation pathway, timing, and preservation potential is essential for accurately interpreting (paleo-)magnetic records in sediments containing this ferrimagnetic mineral. A 6-meter-long sediment core from the Ångermanälven River estuary in northern Sweden provides a clear example of its presence. Using various rock magnetic techniques—including hysteresis loops, FORCs, temperature-dependent susceptibility analysis, and magnetic parameters such as susceptibility ($\chi$), anhysteretic remanent magnetization (ARM), natural remanent magnetization (NRM), and isothermal remanent magnetization (IRM)—we characterized the sediments' magnetic properties and depositional conditions.

While the estuarine sediments are primarily composed of multi-domain (MD) detrital magnetite with a fraction of non-interacting single-domain (SD) grains possibly of biogenic origin, certain layers exhibit magnetic properties indicative of authigenic greigite. Two such layers, at 143 cm and between 500–600 cm depth, show elevated magnetic concentration parameters and acquire a gyroremanent magnetization (GRM; Stephenson, 1980) during AF step demagnetization—a known characteristic of greigite-bearing sediments (Snowball, 1997). Additionally, FORC diagrams also display signatures of authigenic greigite (Roberts et al., 2000), while temperature-dependent susceptibility analysis further confirms the presence of iron sulphides. These findings suggest that the sediments successfully recorded the natural remanent magnetization (NRM), making them reliable magnetic field recorders. However, the presence of greigite introduces complexity into the paleomagnetic record.

## AS25-0760

# The three "Ms" of absolute palaeointensity determination: modelling, microscopy and machine learning

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Determining the strength of Earth's ancient magnetic field (palaeointensity) is notoriously challenging. Experiments to determine the palaeointensity are built on assumptions taken from Néel's thermomagnetic theory, proposed circa 1940, which assumes that the particles that carry the magnetization in a rock are very small (< 100 nm) and uniformly magnetized or "single domain" (SD). Larger particles violate these assumptions, leading to biased results, which are rejected from analyses using selection criteria, with high failure rates (>75%) being common. There is no theory that describes the behaviour of non-SD particles in experiments, so selection criteria are based on phenomenological descriptions of the data. This has led to a wide variety of experimental protocols and criteria, which may be better or worse at dealing with experimental failure.

We detail three new approaches that we are taking to improve the accuracy of absolute palaeointensity determination. First, we have developed new micromagnetic modelling software that can simulate the behaviour of non-SD particles in experiments, paving the way for a new, palaeomagnetic theory. Second, advances in microscopy allow us to image the magnetic carriers in our samples, which we are using as inputs into these micromagnetic models. Finally, techniques from machine learning and statistical modelling can predict the bias of an individual palaeointensity experiment, allowing us to obtain results from specimens which would previously have been rejected. Combining these techniques has the potential to revolutionize palaeointensity research, enabling us to acquire high-fidelity records of our magnetic field strength through the entirety of Earth's history.

## AS25-0823

# Secular Variation in Southeastern Brazil over the past five centuries

*Luiza Gualter Ramires[1], Gelvam André Hartmann[1], Wilbor Poletti[2], Barbara B. Caprara[1], Renata N. Alves[3], Daniel A. Coppi[1], Marcelle Mandarino[3], Maria Dulce Gaspar[3], Marcos André Torres de Souza[3], Ricardo I.F. Trindade[4]*

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The secular variations of Earth's magnetic field, which can span hundreds to thousands of years, reflect changes in both intensity and direction, providing valuable insights into the planet's structure and behavior. One notable feature in the Southern Hemisphere is the South Atlantic Magnetic Anomaly (SAMA), which is characterized by unusually low magnetic field intensities at the Earth's surface. However, understanding of this anomaly remains limited due to the scarcity of data from the region. This study, part of a master's thesis, contributes to expanding the database by presenting six new high-quality archeointensity measurements from brick fragments in Southeastern Brazil. Using the classical TT-ZI protocol, with partial checks for temperature and magnetic mineralogical changes, as well as corrections for anisotropy and cooling rate effects, a 54% success rate was achieved. The results further support the ongoing decline in magnetic field intensity and the influence of the SAMA over Brazilian territory, showing a decrease from approximately 39 μT around 1740 ± 50 CE to about 27 μT in 1918 ± 2 CE. South American archeointensity data for the past five centuries, along with Brazilian speleothem data spanning nearly two millennia, raises intriguing questions, particularly regarding the non-dipole oscillatory behavior of the magnetic field. This underscores the need for continued data collection to enhance our understanding of magnetic field changes.

## AS25-0833

# Magnetic fabric development in Palaeogene rocks of the Podhale Synclinorium (Inner Western Carpathians)

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Anisotropy of Magnetic Susceptibility (AMS) has proven to be a sensitive proxy for quantifying the direction of tectonic strains (eg. Parés, 1999). While AMS is typically imprinted in soft sediment during the early deformation, the extent to which fabric development continues after compaction and cementation remains poorly understood.

In this study, we investigated the Palaeogene rocks exposed in the northern limb of the Podhale Synclinorium (Poland and Slovakia). The siliciclastic strata belong to the northernmost section of the Central Carpathian Palaeogene Basin, which lies within the Inner Carpathians. The main aim of the study is to elucidate the relationship between magnetic fabric and development of joints, folding and faulting.

The analysis of structural data and magnetic samples collected at 12 outcrops along the Kacwinianka stream reveals predominance of the oblate-shaped AMS ellipsoid with a triaxial arrangement. These results point to modification of the initial sedimentary fabric due to horizontal shortening during the formation of the Podhale Synclinorium. However, an in-depth investigation has shown that magnetic lineations tend to align with the strike of longitudinal joints, typically interpreted as extensional structures (Ludwiniak, 2010). A shift from magnetic foliation to lineation and the presence of multiple subfabrics in the AMS indicate tectonic overprinting related to faulting.

The results raise questions about the specific deformation stages associated with AMS fabric development and whether it can effectively record the paleostress field rotation in the studied area, particularly regarding changes in directions of minimum and intermediate stress ($\sigma_3$ and $\sigma_2$).

## AS25-0887

# Magnetic, mineral and porosity fabrics reflecting magma flow in Quaternary lavas of Cartagena (SE Spain)

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Two distinct Cenozoic magmatic phases are recognized in several central-western Mediterranean regions, including Morocco, Spain, France, and Sardinia. In the Betic Cordillera (SE Spain) extensive subduction-related volcanism took place during the Miocene. The Pliocene is a period with no significative volcanisms. Then, around the Plio-Quaternary limit a basaltic volcanic suite was deposited in the Cartagena region. The aim of this work is to reconstruct magma flow dynamics of this younger episode. We integrated analyses of structural markers (elongated vacuoles), magnetic fabrics (anisotropy of magnetic susceptibility, AMS), and mineral fabrics (thin sections) from 21 sampling sites, yielding a total of 269 samples. These samples come from both lava flows and vents. These basalts are characterized by high magnetic susceptibility (1000–60000 x $10^{-6}$ SI), with thermomagnetic curves indicating a fabric with a ferromagnetic origin, probably controlled by various magnetite phases. The results reveal: (i) a predominant N-S magnetic lineation, aligning with the inferred flow directions from volcanic edifices; (ii) a secondary E-W lineation; and (iii) vertical lineation within source areas. The magnetic foliation exhibits greater variability, with poles distributed along a great circle orthogonal to the magnetic lineation. Furthermore, there is a consistency between the AMS-derived flow directions and the orientations of anisotropic vacuoles and mineral fabrics.

## AS25-0992

# Unexpected palaeomagnetic properties of Waikato intraplate and arc basalts, New Zealand

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As part of a quest for southern hemisphere palaeointensities spanning the past few million years, unoriented samples were taken from 44 sites in the Alexandra, Ngatutura, South Auckland and Auckland volcanic fields in the west of New Zealand's North Island, with oriented block samples being taken at 24 of these. Most sites had been K/Ar dated some time ago, and some early assessments of geomagnetic polarities were also available. Previously published geochemical analyses show an unusual mixture of basalts of intraplate and arc origin.

Successful palaeointensities were obtained from only ten of the sites, alteration being the main reason for failure. Thermomagnetic experiments (magnetic susceptibility vs. temperature) showed two very different behaviours. Type 1 samples have irreversible curves with initial Curie temperatures below 200 °C, but alteration products with Curie temperatures around 580 °C on cooling after heating to 700 °C. By contrast, Type 2 samples showed reversible behaviour, with Curie temperatures close to 580 °C on both heating and cooling. A few samples showed a hybrid style of behaviour. Curiously almost all samples produced good thermal demagnetization data, that were compatible with alternating field results well beyond the Curie temperatures of Type 1 samples. Only Type 2 samples yielded successful palaeointensities.

Intraplate basalts are known to be relatively rich in titanium. We account for the observed Type 1 behaviour in terms of an initial remanence-carrier with titanomagnetite to titanomaghaemite composition, that is altered through phase-coupled oxidation during thermal demagnetization, maintaining the direction of the characteristic remanence but compromising the integrity of palaeointensity determinations.

## AS25-1053

# Biogenic and diagenetic greigite in postglacial Baltic Sea sediments

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Greigite, a ferrimagnetic iron sulfide, forms via biogenic mineralization or diagenetic processes in anoxic environments. It is known to contribute to the natural remanent magnetization (NRM) of sediments, complicating the interpretation of paleomagnetic data. As an intermediate phase during pyritization, greigite is crucial to sulfur, iron, and carbon cycles and serves as an environmental indicator of past redox conditions. The Baltic Sea provides an ideal setting to explore greigite formation processes, through its postglacial history, characterized by alternating freshwater and marine phases with recurrent periods of hypoxia. Here, we report on the occurrence, distribution of biogenic (magnetosomal) and diagenetic greigite in Holocene sediments from the Baltic Proper, a currently euxinic basin in the central Baltic Sea. Using paleo- and mineral magnetic analyses including first-order reversal curves, we distinguish between greigite of different origins. Biogenic greigite, with magnetically soft single-domain properties, is present throughout the postglacial sediment sequence, and is dominant in organic-rich laminated horizons (sapropels) that formed during periods of hypoxia during the still ongoing Littorina phase of the Baltic Sea. Diagenetic greigite is confined to horizons coupled to earlier marine-lacustrine transitions. It has harder magnetic properties, acquiring gyro remanent magnetization. Diagenetic greigite horizons exhibit the highest magnetic recording efficiency, with NRM to anhysteretic remanent magnetization (ARM) ratios approaching 1, consistent with chemical remanent magnetization seen in laboratory experiments. While NRM/ARM may not be a reliable paleointensity indicator in greigite bearing sediments, it reveals valuable insights into changes in the magnetic recording mechanisms and aids in identifying diagenetic greigite.

## AS25-1115

# Geomagnetic excursions over the last 33,000 years: a speleothem record from the Moomi Cave, Socotra Island, Yemen

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In the past 33 thousand years (kyr), a number of geomagnetic excursions have been proposed by numerous authors. These include the Mono Lake (~31–34 kyr), Rockall and Lake Mungo (~26 kyr), Hilina Pali (~19 kyr), Tianchi (~17 kyr, revisited to ~10 kyr), Gothenburg (~12 kyr), and Sterno-Etrusso (~2.7 kyr). However, there is still a debate regarding the acceptance of these events as geomagnetic excursions. In this study, we examine the paleomagnetic record of a stalagmite from Moomi Cave on Socotra Island, Yemen. The M1–4 stalagmite was dated using the U-Th methodology, yielding ages ranging from 33.600 (±336) kyr B.P. to 10.773 (±150) kyr B.P. Alternating field demagnetization revealed a viscous secondary magnetization that was cleaned below 12 mT, followed by a primary magnetization pointing to the origin. The magnetic vectors exhibited an average relative declination of 350° and a mean inclination of 30°. Despite the absence of in situ orientation of the stalagmite, the magnetic inclination is consistent with the present-day Earth's magnetic inclination at the Moomi Cave locality. A brief variation of the PSV ranging from 62° to 85° in paleolatitude and from 312° to 104° in paleolongitude is observed at the base of the stalagmite and is interpreted as corresponding to the Mono Lake excursion. The corresponding virtual geomagnetic pole path is consistent with previously published models, based on sediment magnetic properties.
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## AS25-1116

# A Participative Science Project for the Biomonitoring of Vehicular Air Pollution in Cities : the Ecorc'Air project

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Air pollution is a major concern for experts, public authorities and city dwellers, who are the most directly affected. Airborne particulate matter (PM) is indeed well known for its adverse health effects. However, urban air quality stations are too sparse to provide a detailed picture of the pollution distribution. Since PM is deposited on the surface of urban trees, tree bark can act as an excellent witness and an alternative passive trap. We estimate the amount of PM on tree bark by measuring magnetic properties of metallic nanoparticles released by traffic. Here we present the citizen science project Ecorc'Air, in which volunteers collect samples of plane tree bark each spring, in Paris and other French cities, as well as in European cities (Amsterdam, Berlin). Since the launch of this project in 2016, we have measured more than 5,200 samples resulting in the creation of annual maps that depict the fine-scale distribution of metal particles. The concentration of fine metal particles decreases as the distance between trees and the road increases, with parked cars potentially acting as barriers to protect pedestrians from PM. There is a growing interest and involvement of city dwellers, especially those involved in local associations, to act in favor of environmental research. This year (2025), the Ecorc'Air participatory project is evolving and focusing on particulate pollution in schools and nurseries with the Nanomap project and the involvement of local environmental associations.

## AS25-1160

# Deep drilling and near-surface investigation on the formation and destruction of Magnetite clusters beneath the PACMANUS hydrothermal vent field

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Hydrothermal fluid circulation is a key process that affects the chemical composition of seawater and sustains deep-sea ecosystems along the spreading axis. It is also known to cause fluid-rock interaction, which leads to the formation of massive sulfide deposits. While this process has been widely studied, investigations on subsurface structures and processes occurring beneath hydrothermal vents could only be done indirectly. To overcome these limitations, Ocean Drilling Program (ODP) leg 193 drilled the PACMANUS hydrothermal vent field which is located along the eastern Manus Basin, Papua New Guinea. A total of four sites (1188, 1189, 1190, 1191) were drilled during the expedition, with an average recovery rate of 5–10%. Despite the difficulties of drilling through young, fractured volcanic rocks, depths of 387 mbsf and 207 mbsf could be reached at sites 1188 and 1189. Rock magnetic measurements and SEM observations were performed on samples collected from these sites both during and after the expedition. In general, samples were highly altered due to the interaction with seawater and show extremely low magnetic signatures. However, we found samples of unusually high magnetic intensity (50–100 times that of surface basalts) along the depth of around 190 mbsf in both Sites 1188 and 1189. SEM observations show that they contain numerous clusters of single-domain magnetites and titanomagnetites. It appears that they were produced by the intrusion of magmatic fluids with high Fe concentration. We also explore the possibility of detecting such metallic pockets using seafloor survey methods such as deep-tow magnetometer by geophysical modelling.

## AS25-1179

# Age dependent variation of the magnetic fabric of dike swarms from Maio Island, Cabo Verde. Implications for the volcanic structure

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We studied 27 dikes from the Island of Maio, intruding formations from lower Cretaceous to Miocene. The 40Ar/39Ar ages of the studied dikes range from 11.28 ± 0.21 Ma to 9.24 ± 0.49 Ma. Magnetic susceptibility (MS) spans between 10 × 10–3 SI and 110 × 10–3 SI. Dikes intruding the oldest formation show the highest range of MS values while all the remaining dikes show a narrow range of MS values. Magnetic fabric is normal with no imbrication in the margins. Magnetic anisotropy is low except for the dikes of Casas Velhas formation where it is very high. Image analysis of mineral fabric show the magnetic lineation close to the preferred orientation of the phenocrysts. The deduced magmatic flow is predominantly vertical to sub-vertical. The differences observed between Miocene dikes and all other dikes may be explained by sourcing from two distinct magma reservoirs: a shallow source, explaining the very high values of the magnetic anisotropy and the vertical magma flow and a deeper source located in a central position in the island, responsible for the dikes intruding the remaining formations. Magnetic and mineralogical variability in dikes from Batalha formation is interpreted as resulting from a wider age range of the intrusions, compatible with the older age of Batalha fm.

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## AS25-1184

# Magnetic biomonitoring of airborne metallic particles on cultural heritage—The Jerónimos Monastery, Lisbon, Portugal. Preliminary Results

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It is well-known that cultural heritage within urban contexts is threatened by air pollution, that affects both outdoor and indoor artistic assets. Biomonitoring of airborne particulate matter in cultural heritage is a pioneering strategy of Preventive Conservation for damage prevention. While lichens are well established as biomonitors of outdoor particulate matter, its indoor use remains understudied. In this study, indoor magnetic biomonitoring was applied at the Jerónimos Monastery in Lisboa, a UNESCO world heritage site of the early 16$^{th}$ century, as a prime example of religious Manueline architecture, with much of the design characterized by elaborate sculptural details and maritime motifs. Thallus of Parmotrema perlatum were transplanted for 11 weeks to inside the Jerónimos Monastery and Church, to be compared to those exposed in the nearby trafficked road. The outdoor samples exposed at the street and at the exterior facades of the Monastery and Church showed a moderate enhancement of mass-specific magnetic susceptibility values that were 1.3 to 2.1-folds those unexposed. Indoor samples generally showed a lower magnetic enhancement, with the exception of some sites located near the Church entrance. High field magnetic analysis and hysteresis properties showed the presence of vehicular magnetite-like particles. The use of lichen transplants is a suitable method to evaluate outdoor and indoor distribution of airborne PM in highly significative cultural heritage building.

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## AS25-1195

# Environmental legacy of the early modern artillery fortifications: soil contamination recorded by magnetic susceptibility and elemental concentrations

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Warfare activities have detrimental effects on terrestrial ecosystems, including soil environments. However, there is a significant gap in the soil geochemistry of pre-20$^{th}$-century war zones. Hence, four artillery fortifications from the War of the Bavarian Succession (1778) in northern Bohemia were investigated. Soil cores from the interior area of the fortifications, control sites, and bedrock samples were studied for magnetic susceptibility determined using Kappabridge MFK1-FA. Same samples were analyzed for elemental concentrations by using portable X-ray fluorescence (pXRF), which outcomes were validated by Inductively Coupled Plasma (ICP). The contamination levels were evaluated using the geo-accumulation index ($I_{geo}$). Anthropogenic vs. geogenic magnetic contributions were assessed. The fortification subsoil reveals elevated concentrations of arsenic (As), manganese (Mn), sulfur (S), and zinc (Zn). Recent contamination from the Turów brown coal-fired power plant was identified in the topsoil by an increased content of S (2800 ppm determined by ICP). The principal component analysis validated relationships between key elements. The association between Pb, As, S, and P reflects historical contamination. The specific links between magnetic susceptibility parameters and elemental concentrations imply soldier activities such as waste disposal (increased levels of Ca and Mn), burning and excrements (P and Zn), or black gunpowder usage (Significant S enrichment in the subsoil). This study provides new insights into the environmental legacy of former warzones and suggests that warfare before the 20$^{th}$ century also resulted in a measurable environmental burden.

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## AS25-1207

# A multi-proxies record of the late Quaternary climate variability from the lacustrine Castiglione maar sequence (central Italy)

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The AMUSED project (A MUltidisciplinary Study of past global climatE changes from continental and marine archives in the MeDiterranean region, https://progetti.ingv.it/index.php/it/amused) aim to investigate the middle-late Quaternary climate variability by integrating multi-proxy data acquired in different geological settings. In this context, we investigated the Castiglione maar (Colli Albani volcanic district in central Italy) by drilling the lacustrine sequence succession. Following geophysical exploration, two parallel drill sediment sequences were recovered from the central sector of the basin. The sedimentary infilling consists of fine-grained sediments: mainly fine sand, silt and clay, with minor gravel intervals and numerous tephras deriving from explosive eruptions of the Roman Province volcanoes such as Mt. Vulsini, Vico, Mt. Sabatini and Alban Hills. A total of 55 volcanic layers were identified and used, together with the lithostratigraphic features, for correlating the two drill sites and reconstruct the 131.2 m long Castiglione composite section. Combining new and available $^{40}Ar/^{39}Ar$ ages from the literature, we reconstructed the age model by applying the Bayesian statistical method to the succession, resulting in a continuous sequence spanning the last 365 ka with a mean sedimentation rate of 0.33 mm/yr. We present high-resolution and geochronologically well-constrained multi-proxy records for the entire succession. The high-resolution X-Ray Fluorescence scan data, TIC-TOC-TC and the paleomagnetic and rock magnetic analyses built the information on the MIS 1–MIS 10 climate dynamics in the peri-Tyrrhenian setting.

## AS25-1219

# The past and future of archaeomagnetism in the Czech Republic

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Archaeomagnetism provides sufficient data to understand the evolution of Earth's centennial to millennial timescale magnetic field. Many studies have been published on European directional and intensity data. However, in the Czech Republic, only limited data were published almost 30 years ago, and since then, there has been no actual development of the archaeomagnetic method. As a result of improved collaboration between archaeomagnetists and archaeological institutions in Czechia, we can investigate a new collection of burnt material for archaeomagnetic study. Since 2021, samples have been taken from ~60 burnt structures from 18 sites. This collection includes wide time interval from ~6000 BC to ~1700 AD. Step by step, a new local secular variation curve for the Czech Republic based on directional data will be assembled.

Here, we present an archaeomagnetic study with detailed magneto-mineralogical results from a medieval bakery oven (Vinoř site). Furthermore, the spatial and age distributions of existing data and newly collected burnt objects from Czechia will be presented, and already obtained directional data from a few sites will be compared with the available data from neighbouring countries and with global models.

## AS25-1222

# Cave sediments reveal neotectonic vertical-axis rotations in the Adria-Eurasia collision zone, Slovenia

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We use paleomagnetic data obtained from cave sediments to document neotectonic (0–5 Ma) vertical-axis rotations in the northeastern corner of the Adria-Eurasia collision zone. Magnetostratigraphy, radiometric dating, biostratigraphy, and geomorphologic constraints were combined to establish a robust chronology in the spatially and temporally highly discontinuous sediment record preserved in karst areas. We distinguish two tectonic domains from the rotation patterns: the Adriatic coastal thrust belt which exhibits early clockwise, probably syn-emplacement rotation, followed by post-1.5 Ma counterclockwise rotation, and the continental interior which displays persistent counterclockwise rotation suggesting domino-like rotation of rigid blocks bounded by NW-SE-trending faults. Inferred block rotation rates range from 2 to 10°/Ma, which is compatible with published Quaternary fault-slip rates and with the regional shortening rates derived from GNSS geodesy. Our paleomagnetic data show that the northeastern peri-Adriatic belt is fully detached from the Adria microplate, which itself rotates <0.5°/Ma in a counterclockwise sense.

## AS25-1224

# Measurements of Earth's magnetic field anomalies caused by meteorite impacts

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Meteorites that have impacted the Earth's surface in the past have created impact craters. Most of these craters have not been preserved in a form that allows for their contemporary identification, but some, especially in Central and Northern Europe, have been described and classified as geological structures formed by meteorite impacts.

When a celestial body strikes the Earth's surface, it causes a temporary increase in temperature to several hundred degrees Celsius, sometimes exceeding the Curie temperature for ferromagnetic rocks and minerals that make up the near-surface layer. The impact leads to a change in the direction of magnetization in the minerals, which sometimes persists after the impact. This phenomenon is known as Thermoremanent Magnetization (TRM). It is characteristic of meteorite impact sites. The project aims to conduct research in the field of applied geophysics and the magnetic properties of rock and mineral samples in the area of craters formed by meteorite impacts in the context of thermomagnetic anomalies.

As part of this project, proton magnetometer measurements have been conducted in the areas of the Morasko craters in Poland, the Dobele crater in Latvia, the Vepriai crater in Lithuania, and several craters in Estonia. The results of the magnetometric measurements are very promising and exhibit characteristic patterns of magnetic field anomalies typical of impact craters.

The project is funded under the 'Pearls of Science' program by the Ministry of Science and Higher Education of the Republic of Poland.

## AS25-1346

# Paleomagnetic shallowing on lava flows

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This study investigates the inclination shallowing observed in paleomagnetic directions from lava flows, focusing on its possible causes. While non-dipole contributions to Earth's magnetic field and incomplete recording of paleosecular variation are commonly cited, this research highlights the role of lava flow anisotropy. A detailed analysis was conducted on four historical basaltic lava flows from the Azores (Terceira and Pico islands), incorporating paleomagnetic studies, anisotropy of magnetic susceptibility (AMS), anisotropy of anhysteretic remanence (AARM), and petrographic observations. The results indicate that sites with low anisotropy (Pj < 1.03) exhibit well-grouped paleomagnetic directions, following a Fisher distribution. In contrast, sites with higher anisotropy (Pj up to 1.15) show triaxial AMS ellipsoids and paleomagnetic directions with an ellipsoidal distribution. The AMS and AARM ellipsoids display similar orientations, with their anisotropies showing a linear correlation. Petrographic observations confirm a flow-related anisotropy consistent with these findings. For highly anisotropic lava flows, paleomagnetic inclinations deviate by up to 20° and show an inverse correlation with anisotropy, while declinations shift in accordance with the maximum AMS axis orientation. These results suggest that petrographic anisotropy can significantly affect paleomagnetic directions in basaltic rocks, emphasizing the importance of preliminary rock fabric analyses for accurate paleomagnetic studies.

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## AS25-1349

# North Atlantic Ocean—Low latitude archaeomagnetic data (Fogo Island, Cabo Verde Archipelago)

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This study investigates the secular variation of Earth's magnetic field in low-latitude volcanic oceanic islands, focusing on Fogo Island in the Cabo Verde Archipelago. Fogo's active Quaternary stratovolcano, with 28 eruptions since 1460 A.D., provides a valuable record for paleomagnetic analysis. A total of 40 historical and prehistoric lava flows, covering 57 sampling sites around Chã das Caldeiras and the island's eastern flank, were studied. Rock magnetic and petrographic analyses identified titanomagnetite phases as the primary magnetic carriers, with minimal alteration. The low anisotropy of magnetic susceptibility (AMS) suggests no significant distortion in paleomagnetic directions. Thermal and alternating field demagnetization methods successfully isolated well-clustered characteristic remanent magnetization (ChRM) directions. Comparing 12 ChRM directions from historically mapped lava flows with secular variation models confirmed the expected ages for nine flows, while three were reclassified as prehistoric. Additionally, ChRM directions from prehistoric flows closely follow known secular variation curves, contributing to refining the island's volcanic stratigraphy and improving secular variation models. This research has been funded by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) – (https://doi.org/10.54499/UIDB/50019/2020), UIDP/50019/2020 and LA/P/0068/2020 (https://doi.org/10.54499/LA/P/0068/2020). This work is a contribution to projects REGENA (Ref. PTDC /GEO-FIQ/3648/2012) and GEMMA (Ref. PTDC/CTA-GEO/2083/2021).

# A03 Planetary magnetic fields and secular variations on all temporal and spatial scales

## AS25-0169

## Refining secular variation in Central Europe with archeointensities from the Bronze to Iron Age transition and the Early Medieval Ages

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The paleomagnetic analysis of archeological materials allows to reconstruct the variations of the Earth's magnetic field over the past millennia. Knowledge about these variations is crucial for understanding the geodynamo and is used for dating approaches.

Geomagnetic field variations during the Early Medieval Age (EMA) and the Bronze to Iron Age Transition (BIAT) in Central Europe are generally poorly constrained due to the scarcity of archeological sites. In other regions, strong and rapid variations of the field strength were observed during these intervals. New archeointensity data from Central Europe is thus needed in order to reconstruct more closely the spatio-temporal evolution of these field features.

In this study, archeological samples, mainly potsherds, from Germany, Austria and Poland (EMA: 500 to 1000 AD) and Austria, Bosnia, Germany and Serbia (BIAT: 1300 to 750 BC) were investigated. Archeointensities were determined using the MT4 protocol, including pTRM, tail checks and additivity checks, along with corrections for anisotropy and cooling rate effects. Accepted specimen values have been selected with modified Thellier Tool criteria sets A and B. For specific sites, the multi-specimen domain-state corrected (MSP-DSC) protocol was also used. Obtained paleointensity results agree with those from Thellier. Rock magnetic experiments comprised hysteresis, backfield curve and FORC measurements.

For the BIAT period, the archeointensity values range from about 40 to 80 µT and suggest a sharp increase of archeointensity around the Bronze to Iron Age transition. For the EMA period, we measured lower values than in Western Europe, around 50 µT.

## AS25-0203

# Greigite formation in Dutch Holocene levee systems

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Lake IJssel has a complex Holocene history. The region shifted several times between a terrestrial, riverine, subtidal, intertidal, lacustrine, and lagoonal environment. Extensive magnetometer surveys of the lake bottom revealed curvy magnetic lineations evocative of river/tidal channels. Vibro-cores were recovered to investigate the magnetic signal's source. Previous core samples (from 2022) showed the magnetic mineral greigite ($Fe_3S_4$). One core, VC26, was resampled in 2024 in high resolution (~2.5 cm spacing). Focus was on whether the greigite formed biogenically or early diagenetically with implications for interpreting the NRM (natural remanent magnetization) record. By comparing 2024 data to similar 2022 data the effect of cold storage on the magnetic signal can be assessed. After alternating field demagnetization of the NRM acquisition curves of the anhysteretic and isothermal remanent magnetization were measured. First order reversal curve (FORC) analyses can distinguish between diagenetic and magnetotactic greigite. A paleosecular variation and a relative paleointensity record (with the pseudo-Thellier method) were established for core VC26. Comparing the 2022 and 2024 data show that the amount of magnetic material went down, yet the NRM directions were consistent. FORC-data made it clear that while secondary authigenic greigite is present, the main source is magnetotactic greigite. Thus, the NRM signal is only slightly younger than the sediments themselves and the record can be used for paleosecular variation analysis. Interpretation of the relative paleointensity record is less straightforward. Comparison to master curves and integrating with $^{14}C$ dates showed that VC26 sediment was formed between 7.2 and 4.5 ka BP.

## AS25-0249

# Accessing the dipole-multipole transition in rapidly rotating spherical shell dynamos

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Earth's magnetic field has exhibited erratic polarity reversals over much of its history; however, the processes that cause polarity transitions are still poorly understood. Dipole reversals have been found in many numerical dynamo simulations and often occur close to the transition between dipole-dominated and multipolar dynamo regimes. However, the physical conditions used in reversing simulations are necessarily far from those in Earth's liquid iron core. Here, we develop a unidimensional path theory in an attempt to simplify the search for the dipole-multipole transition at increasingly realistic physical conditions. We consider three paths built by requiring a constant magnetic Reynolds number Rm; one path further imposes balance between Magnetic, Coriolis, and Archimedean forces (MAC balance) while the others constrain solutions to an inertia-MAC, or IMAC, balance. Simulations show reasonable agreement with the expected physical conditions along the paths within the accessible parameter space, but also deviate from predicted behaviour for the magnetic field strength and magnetic/kinetic energy ratio. Furthermore, simulations move into the dipolar non-reversing regime as they are advanced along the path. By moderately increasing the Rayleigh number above values predicted by the path theory, we access the dipole-multipole transition down to an Ekman number Ek~1e-6, comparable to the most extreme conditions reported to date. Our results therefore demonstrate that the path approach is an efficient method for seeking the dipole-multipole transition in rapidly rotating dynamos. However, the conditions under which we access the dipole-multipole transition become increasingly hard to access numerically and also increasingly unrealistic.

## AS25-0251

# Modelling and observing hydromagnetic modes

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Hydromagnetic modes (global waves) can propagate through the Earth's liquid core. Rapid rotation and the presence of the magnetic field allow for a broad family of modes at periods over days to millennia. Some of these modes, with periods longer than a few years, may cause significant oscillations in geomagnetic observations. The state of the core, over which these modes propagate, can have strong implications on the properties (frequency, damping rate, spatial structure) of the modes. I will discuss the impact of the background magnetic field and flow on the properties of Magneto-Coriolis modes at a range of periods and how it can affect their geomagnetic imprint.

## AS25-0270

# Geomagnetic secular variation from the East Sulawesi Ophiolite (Banggai Regency, Indonesia)

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The East Sulawesi Ophiolite (ESO), thought to be emplaced in the Late Cretaceous, is one of the three largest ophiolites in the world. Its upper section consists of an ~1 km-thick sequence of basaltic flows that preserve palaeomagnetic records, providing insights into its palaeogeography and the behaviour of the Earth's magnetic field towards the end of the Cretaceous Normal Superchron (CNS; 121–84 Ma), an enigmatic 40-Myr period during which the Earth's magnetic field stopped reversing its polarity.

We collected palaeomagnetic samples from 230 lava flows in the Balantak (Batumandi, Teku, Pulo Dua), Toili, and Siuna districts. For each flow, we drilled 8–10 cores and oriented them using a sun compass to avoid misorientation errors due to magnetic anomalies. Systematic alternating field demagnetisation of the samples was conducted using the automated "sushibar" system with an embedded high-precision cryogenic magnetometer, supplemented by thermal demagnetisation of three sister samples per flow to ensure the robustness of the palaeodirectional data.

Based on the analysis of the distribution of palaeodirections derived from the 230 lava flows, we intend to provide a new estimate of the dispersion of the virtual geomagnetic poles at the end of CNS. This value will be compared with other available estimates over the past 120 Myr in order to better characterise the geomagnetic secular variation and the state of the geodynamo. In particular, we will address the controversial issue of the dependency between secular variation and reversal rate over the past 120 Myr.

## AS25-0325

# A new global model for the Holocene geomagnetic field

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Studies of the global magnetic field over millennial timescales rely on paleomagnetic data from thermoremanent and sedimentary sources. However, both data types suffer from uneven spatial coverage, measurement errors, and dating uncertainties. In recent years, Bayesian models have been developed to reconstruct the Holocene geomagnetic field, addressing these challenges and incorporating uncertainties into the posterior distribution.

Based on recent advances in tackling the non-linearity of the inverse problem and the non-Gaussian error distributions via Markov chain Monte-Carlo, we will present a new global model for the Holocene geomagnetic field. We discuss the selection of prior parameters and the impact of different choices. We compare our results to existing models, with particular attention to model uncertainties.

## AS25-0498

# Paleomagnetic Secular Variation of Early-Middle Miocene Volcanics from Vogelsberg (Germany)

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The Earth's magnetic field significantly changed its rate of polarity reversals over the past 200 Myr; yet it remains controversial whether these drastic changes-from a stable state of polarity during the Cretaceous Normal Superchron to more than 10 events per Myr during the Jurassic-are accompanied with similar changes in the directional variability of the field, termed paleosecular variation (PSV). In an effort to better constrain the geomagnetic behavior during the Miocene, we investigated the paleomagnetism of 162 volcanic units (1920 cores) from the Vogelsberg, the largest volcanic mountain range in Central Europe emplaced between 17.6 and 15.2 Ma. We successfully interpreted the paleodirections of 148 volcanic units, which led to a final collection of 127 independent geomagnetic records after correction for serial correlation. After removing the transitional directions, this collection passes the reversal test and yields a paleomagnetic pole located at 161.9˚ E and 84.5˚ N (A_95 = 3.2˚, N = 116), which is statistically indistinguishable from the predictions of the latest apparent polar wander paths for stable Europe. Used as a proxy for PSV, the dispersion of the virtual geomagnetic poles S_B = 19.1˚|_(17.5˚)^(20.8˚) (N = 116) is consistent with a more variable paleomagnetic field during the Miocene relative to the past 10 Myr, as recently proposed from the analysis of the global PSV database. However, when focusing on the paleolatitudinal range 40–50˚ over the past 200 Myr, we failed to detect a robust correlation between S_B and the rate of polarity reversals.

## AS25-0509

# New archeointensity results from ~7 ka in Eastern China and their constraint on the regional variations of the geomagnetic field

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Archeomagnetism, a subject applying the paleomagnetic principles and methods to baked archeological materials, has become the primary method for reconstructing the high-resolution variations in the geomagnetic field during the Holocene since its foundation in the 1950s. China hosts numerous archeological sites, offering advantageous opportunities for archeomagnetic research. However, the existing archeomagnetic data in China remain scarce, and more than half of them were published in the 20$^{th}$ century with varying levels of data quality. This limits the resolution and accuracy of regional geomagnetic reference curves in the area. In this study, we carried out archeomagnetic research on two Neolithic archeological sites in Eastern China and obtained reliable archeointensity results. Our new data provide reliable anchors for the intensity variations in Eastern Asia during the poorly constrained time period before 4000 BCE. The results show a fast-changed geomagnetic field, with virtual axial dipole moments varying from ~56 to ~91 ZAm$^2$ between ~5350 and 5030 BCE. This inference is further supported by intensities recovered from the double-remanent components of some samples through vector calculations. By adding the new data to the current dataset, we released an updated version of the Chinese archeointensity reference curve (ArchInt_China3), which will provide valuable insights into the regional and global geomagnetic field variations during the Holocene, and thus assist in understanding the dynamic processes in the Earth's interior.

## AS25-0512

# Effect of inner core nucleation on paleomagnetic observables in geodynamo simulations

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The present-day geodynamo is thought to be mostly powered through the crystallisation of the inner core. Though we have evidence showing that the Earth's self-sustained magnetic field has been existing for at least 3 billion years, the timing of inner core nucleation (ICN) remains unknown. Determining the ICN timing would provide crucial constraints on the evolution of the geodynamo and on the Earth's energy budget. Paleomagnetic data can be used to investigate the evolution of the magnetic field. Variations in the intensity and variability of the magnetic field are notably predicted after inner core nucleation. However, the sparsity of the paleomagnetic data combined with a poor knowledge of the imprint of inner core nucleation on the magnetic field is making this hunt for the inner core nucleation timing challenging.

Our goal is to better understand what changes to expect in the paleomagnetic record after ICN. We use geodynamo simulations tuned to represent post-ICN and pre-ICN conditions to compare the magnetic field in both configurations. We exploit previously published thermal evolution models of the Earth to statistically predict post-ICN and pre-ICN conditions relative to the present day. Simulating the geodynamo is challenging due to the extreme conditions in the Earth's core. To alleviate this issue, we present a path approach linking the parameter space of the simulations to Earth's core conditions. This approach has previously been shown to work for present-day conditions, and we extend it for post-ICN and pre-ICN conditions.

## AS25-0513

# On thermochemical convection and thermochemically driven hydromagnetic dynamos at high Prandtl numbers

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Using the PARODY dynamo code, we numerically investigate thermochemical convection and thermochemically driven dynamos in spherical shells. The thermodynamic model is based on codensity, which combines temperature and composition, focusing on cases where chemical convection dominates over thermal convection. Our study examines high Prandtl numbers and further explores the dependence on the Ekman number and buoyancy factor. The results reveal how convection and dynamo action vary with these parameters.

Convection and the resulting magnetic field exhibit a strong dependence on the Prandtl number. As the Prandtl number increases, columnar convection gradually transitions to codensity plume-dominated convection. Despite this transition, the generated magnetic field remains dipole-dominated, though its characteristics and output parameters vary with the Prandtl number. Additionally, as the Ekman number decreases, finer structures emerge in both convection and the magnetic field.

A key feature of convection is the self-consistent formation of a thin, stably stratified layer at the top of the shell, reinforcing the findings of Bouffard et al. (2019). While this layer influences convection, its effect on the generated magnetic field remains negligible. A significantly greater thickness would be required for it to have a noticeable impact, as observed in previous studies.

## AS25-0525

# GEOMAGFOR—Geomagnetic core field forecasting: a case study

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The GEOMAGFOR project aims to explore the potential of AI-based methods to improve geomagnetic field forecasting, with a particular focus on enhancing the accuracy of the International Geomagnetic Reference Field (IGRF) and its predictions (team GFZ Potsdam). Additionally, the project seeks to apply physics-informed AI techniques to develop more realistic models of geomagnetic reversals and excursions (team HZDR). A key objective is to leverage the synergy between GFZ and HZDR by integrating GFZ's short-term geodynamo predictions with HZDR's reconstructions of reversals and excursions, enabling mid-term geomagnetic field forecasting and probabilistic estimates of future excursions or reversals over the coming centuries to millennia.

The HZDR team employs physics-informed neural networks (PINNs) to solve the inverse problem of reconstructing the full dynamics of typical geomagnetic excursions and reversals, as inferred from global reconstructions based on paleomagnetic data provided by GFZ. To achieve this, a 2D α2-dynamo model has been developed within the Dedalus framework, where the model is parameterized by the radial and meridional distribution of the α-effect. AI techniques are then utilized to invert the spherical harmonic coefficients of geomagnetic field models built at GFZ using real paleomagnetic data, specifically from the Laschamps excursion and the last geomagnetic reversal.

This work presents preliminary results from our modelling efforts.

## AS25-0538

# The Laschamps geomagnetic excursion recorded in Portuguese stalagmites

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We present the record of the Laschamp excursion in two stalagmites from the Bat Cave in Central Portugal. The Laschamp is dated at approximately 41,000 ka based on 14C, with a duration of ~1,000 years for the main phase. Paleotemperatures have been calculated using the fluid inclusion hydrogen isotope ($d^2H$) and the calcite-water isotope fractionation paleothermometer. These calculations indicate increased absolute temperatures just before and during the Laschamps, which are strongly correlated with the NGRIP ice core record. The FORC diagrams, IRM curves, and hysteresis parameters indicate that the primary magnetic carrier is non-interacting single-domain magnetite, with a minor contribution from hematite. The magnetic directions calculated after AF demagnetization are well clustered (MAD~4º) into normal, inverse, and transitional polarities. During the excursion, the VGPs delineate a coherent clockwise trajectory originating from the Eastern Pacific Ocean, traversing down to Antarctica, and culminating in a return to the Northern Hemisphere through Africa and Greenland. The relative paleointensities, estimated by the Pseud-Thellier method, demonstrate that the lowest recorded intensities during the Lashamp excursion are associated with the transitional fields. A minor intensity hump is observed in the reverse field, which is analogous to the LSMOD2 PSV model. The data presented herein offer an unparalleled perspective on the Laschamp excursion within the continental record, thereby facilitating a comprehensive investigation into the fundamental nature of the geomagnetic field during this period.

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## AS25-0542

# Comparing geodynamo simulations to geomagnetic observations over multiple timescales

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Geomagnetic measurements (obtained from surveys, observatories, and satellites) along with paleomagnetic data from rock and anthropogenic samples, offer valuable insights into the behaviour of Earth's magnetic field and its time-dependent changes. We want to relate geomagnetic field observations to the dynamics and evolution of the fluid core, which requires dynamo simulations. While geomagnetic and paleomagnetic measurements provide direct observations of the field's behaviour, they are unevenly distributed in time and space, with coverage worsening further into the past. In contrast, geodynamo simulations offer a forward model of Earth's magnetic field with fine spatial and temporal coverage. However, these simulations do not operate within the precise parameter range of Earth's core. To compare the measured geomagnetic field with geodynamo models, several criteria can be applied. On centennial timescales, criteria use the spherical harmonic representation of the global field downward continued to the core-mantle boundary. On millennial timescales, only low-order spherical harmonic models or local time-series are available. For longer timescales, statistical analyses must be employed. While these criteria have been individually used to compare dynamo simulations and field observations they are yet to be combined. Hence, it remains unclear whether certain parameter regimes produce consistent 'Earth-like' results over all timescales. This study aims to integrate various criteria from previous research, applying them to a large and consistent dataset to identify the general conditions under which simulations align with observations. This work will contribute to the IAGA FAIR-MOD WG, which seeks to make geodynamo model outputs available in an international, reproducible database.

## AS25-0546

# The DRESDYN precession experiment: motivation, preparation, and first results

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The most ambitious project within the DREsden Sodium facility for DYNamo and thermohydraulic studies (DRESDYN) at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is the set-up of a precession-driven dynamo experiment using liquid sodium as the working fluid. Its main motivation is related to the potential role of harmonic forcings, such as libration, precession, or tides for the dynamo action in cosmic bodies. We present the results of water pre-experiments at a 1:6 downscaled device and accompanying numerical predictions, and address the numerous structural and design problems of the big machine. Its central cylindrical vessel with a diameter of 2 and the same height is supposed to rotate at 10 Hz and precess at 1 Hz. Some preliminary results of first water experiments at reduced rotation rates will be presented and compared with the predictions.

## AS25-0550

# Evaluation of Archeo- and Paleomagnetic field models and their common features

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Archeo- and paleomagnetic field models show a wide range of temporal variability and of spatial content. While the temporal variability may reflect true geomagnetic field variation, the different spatial content of individual models could be explained by different modeling strategies and data sources, but mostly by data uncertainties. To overcome these data uncertainties, we derive averaged models over the last 100 kyrs from a large suite of different archeo- and paleomagnetic field models using different average techniques. The averaged models allow us to evaluate the robustness and the significance of spatial features of these models throughout time. It is utilized to compute structural criteria that quantify the axial dipole dominance, the equator-symmetry of magnetic field, its zonality and other important measures of weak field regions and control of the geodynamo by heterogeneous heat flux at the lowermost mantle. These criteria are used to quantify the Earth-likeness of numerical dynamo simulations. Over 100 kyrs the criteria show larger fluctuations than previously assumed, which implies a wider range of numerical dynamo simulations to be considered Earth-like.

## AS25-0564

# Mid-stage evolution of the lunar magnetic field revealed by Chang'e returned samples

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The Moon once had a magnetic dynamo that generated its lunar magnetic field. Studying the evolution of this field offers valuable insights into the Moon's internal structure and thermal state. Our current understanding of the Moon's paleomagnetic field largely comes from the Apollo returned samples, which are mainly from periods older than 3 billion years (Ga). Limited data hinder understanding of the lunar dynamo's duration and mechanisms. Some studies suggest that the Moon's magnetic field was once as strong as Earth's and declined to low levels around 3.1 Ga, while others propose the dynamo lasted only 100–200 million years after the Moon's formation. The Chang'e-5 mission returned basalt samples from the Moon's mid-latitudes (43.06° N, 51.92° W), with an eruption age of about 2 Ga, while Chang'e-6 returned first samples from the Moon's farside (41.64° S, 153.99° W), with basalt eruption age of 2.8 Ga. These samples provide crucial opportunity for understanding the mid-stage evolution of the Moon's magnetic field. We carried out palaeomagnetic studies on basalt clasts of the returned samples from both missions. The Chang'e-6 basalts recorded palaeointensities of 5–21 μT, suggesting a possible rebound in the lunar magnetic field around 2.8 Ga, while the Chang'e-5 samples recorded palaeointensities of 2–4 μT, indicating a weak magnetic field existed at 2 Ga. These findings offer important constraints for understanding the Moon's magnetic field evolution and the driving mechanisms of the lunar dynamo.

## AS25-0568

# Geomagnetic field average morphology through deep geological time

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Studying variations in the Earth's magnetic field throughout geological history is crucial for understanding the dynamic processes in the Earth's outer core and its coupling with other layers. Global reconstructions on these timescales can only be achieved when sufficient data are available for a specific time period. Paleomagnetic intensity and directions dating back to 4 billion years ago are compiled in the published PINT database. We have first updated the PINTv8.1.1 database with data coming from 57 publications. In total 1,942 sites with data are added, with 98% of the sites containing directional data. For reconstructing the paleolocations at the time of the acquisition of the geomagnetic field, we employed different plate motion models and tested the reconstructed locations. Paleomagnetic records are sparsely distributed both in time and space and vary in quality. Spatial distribution and data quality are considered as factors in deciding which periods to analyze. Global, time-averaged field reconstructions will be presented accompanied by model variance and resolution showing what is resolved with the data. Available quantitative and statistical parameters, such as from the Giant Gaussian Process models derived for different periods, are compared to the new models. The reconstructed field morphologies over distinct states of the paleomagnetic field and selected geological periods provide observational constraints of the geodynamo.

## AS25-0591

# Evidence of a long-period anomalous geomagnetic feature in the South Atlantic region

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An extensive analysis of geomagnetic field variations over time is key to understanding the evolution of anomalous geomagnetic features. The most important anomalous feature of the present-day geomagnetic field is the South Atlantic Anomaly (SAA), characterized by the lowest intensities observed in the historical and millennial geomagnetic models. However, the longevity of SAA-type structures in the past few million years is a subject of debate, mainly due to the scarcity of paleomagnetic data in the South Atlantic region. Here, we assess the persistence of anomalous sources from the combination of new paleomagnetic records of Trindade Island (Brazil) with analyses of the latitudinal behavior of paleosecular variation (PSV) for the 0–10 Ma interval and synthetic models. The Trindade Island data extend the longitudinal record of the high virtual geomagnetic pole dispersion in the South Atlantic, close to Brazilian territory, and the temporal coverage during the Pleistocene-Pliocene (0.059–3.9 Ma). This new dataset was incorporated into the 0–10 Ma database for the development of regional PSV models that provide evidence of an enduring hemispheric asymmetry in the field structure over the past 10 Myr. Results reveal enhanced PSV activity and a lower average dominance in the Atlantic Hemisphere than in the Pacific Hemisphere. The synthetic models show that the strength and position of geomagnetic flux patches have a strong influence on the latitudinal PSV structure. Our findings suggest that the peculiar behavior of the South Atlantic Anomaly, and the Pacific-Atlantic field asymmetries are likely attributed to long-term heterogeneities in the lower mantle.

## AS25-0616

# Laterally varying heat source distribution enhances regional convective instabilities in rotating spherical shells

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Thermal convection within a rotating spherical shell serves as an essential foundation for understanding the fluid dynamics in molten cores of all planetary interiors. Thermal buoyancy forces in Earth's outer core encounter significant modification when spatially varying thermal conditions are applied. This evolution crucially influences planetary magnetic field generation through geodynamo processes. The impact of boundary heat flux (BH) variation on convection and dynamo action are extensively studied. The present study introduces and investigates a novel mechanism of heat source heterogeneity (SH) as a driving factor for buoyancy forcing in the entire volume of the rotating spherical shell. This mechanism closely mimics the effects of non-uniform secular cooling in the outer core. The most distinguished difference is the capability of SH forcing to significantly regulate the thermo-fluidic state in the entire volume while the BH-driven anomalies are restricted in the region close to the outer boundary only. Dynamically, weak SH-driven anomalies contribute more effectively in thermo-fluidic patterns in comparison to BH cases with stronger variation. SH modifies the reduction in onset threshold, localization of the convective instabilities, concentrated steady thermal winds, the dominance of anti-cyclonic axial helicity and homogenized flow field with smaller scaled spherical harmonic heterogeneity pattern in comparison to homogeneous case. Additionally, a novel phenomenon of dual onset is investigated which shows distinctive transitions in convective instabilities exhibiting larger variations. Furthermore, analyzing the boundary thermal state under SH effects highlights notable aspects of core-mantle and outer-inner core interactions, impacting geophysical processes and planetary thermal evolution.

## AS25-0626

# Archeomagnetic database and field intensity variation curves for South America over the last 5 millennia

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The study of variations in geomagnetic field intensity over time and space is crucial for understanding the evolution of the geodynamo and its interactions with the Earth's surface. In this work, we introduce the SAGEOMAG (South America GEOMAGnetic) database, a comprehensive and updated repository of geomagnetic field intensity records derived from archeological artifacts and volcanic materials over the past 5 millennia. This database adheres to the FAIR principles. A key advantage of the SAGEOMAG database is its inclusion of statistical parameters at the specimen level, as well as the ability to categorize data according to the hierarchical level of record (site, fragment, or specimen). Additionally, we propose new intensity variation curves for South America, modeled using a bootstrap algorithm that minimizes the influence of outliers and estimates the probability density function without needing prior explicit shape considerations. For records lacking intensity and age uncertainty details in the original studies, standard errors were assigned based on Gaussian distributions. Our findings demonstrate that the modeling of master curves is highly sensitive to the quality filters applied to the data and the hierarchical level of each record. This research aims to provide a foundational framework for improving global and regional archaeomagnetic models, thereby enhancing our understanding of the evolution of the geomagnetic field and its intriguing feature, the South Atlantic Anomaly (SAA).

## AS25-0655

# Impact of including temporal and spatial covariance in giant Gaussian process models of geomagnetic paleosecular variation

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Statistical descriptions have long been used in assessing both the quality of paleomagnetic data and paleomagnetic field variability. Here we focus on the latter issue. More than 35 years ago the first Giant Gaussian Process (GGP) models based on proposed independent statistical distributions of the spherical harmonic Gauss coefficients were introduced, providing a means to produce a consistent statistical model that could in principle satisfy both paleomagnetic directional and paleointensity information. Numerous updates and iterations have been attempted to account for geographic variations in overall mean values and standard deviation found in records derived from lava flows. However, success has been limited due to the poor spatial and temporal sampling of lavas available even when the time intervals are restricted to the past few million years. Furthermore, the intrinsic limitations on chronological constraints available for lava flows means additional information is required to account for any temporal correlations in geomagnetic field evolution. These are now well documented in sedimentary records and evident in the frequency dependence of the geomagnetic power spectrum derived from time varying paleofield models. We extend the GGP framework to include both spatial and temporal covariances estimated from global time varying paleomagnetic fields models spanning 0–100 ka. The inclusion of suitable temporal covariance between low degree and order Gauss coefficients produces potentially detectable non-zonal geographic variations in the field.

## AS25-0671

# A ~6-Year Cyclicity in Solar Activity, Earth's Rotation, and Geomagnetic Field Variations: Evidence for a Coupled Mechanism

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This study investigates a ~6-year cyclicity pattern in three key geophysical datasets: solar radio flux (F10.7 index), Earth's length of day (LOD), and geomagnetic field variations recorded at some ground observatories. Using power spectral density (PSD) via the periodogram method and wavelet analysis, we identify dominant periodicities spanning multi-decadal timescales. Analysis of daily solar radio flux across multiple solar cycles reveals a ~*6*-year periodicity alongside the well-established 11-year solar cycle. Similarly, Earth's LOD data (1964–2024) exhibits a dominant oscillation again ~*6*-year , while both hourly and daily mean geomagnetic field measurements of some observatories also show a consistent ~*6*-year periodicity over several decades. The synchronized oscillations observed across multiple datasets suggest a potential coupling mechanism linking solar activity, Earth's rotation, and geomagnetic field variations. The strong spectral coherence across these independent parameters points to a possible common underlying driver influencing these global-scale geophysical processes.

## AS25-0676

# High-resolution records of secular variation using speleothems in Mexico: principles, sampling techniques and preliminary results

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Since the research work of Latham et al. (1986), speleothems have been considered potential archives for studying of Earth's Magnetic Field secular variation (SV). The formation of calcite speleothems involves the precipitation of $CaCO_3$, a process during which speleothems incorporate magnetic minerals into their matrix. There is enough time between particle deposition and crystallization for their magnetic moments to align with Earth's magnetic field (Lascu & Feinberg, 2011). The continuous growth of speleothems may provide a high-resolution time series of SV.

Sampling speleothems is still a challenge for those who want to study SV through them. In the first paleomagnetic study using speleothems works in Mexico, Latham et al. (1986), oriented the speleothems using an aluminium device carrying a Suunto magnetic compass. Recently, Font (personal communication) oriented speleothems in situ using a laser clinometer and a magnetic compass. In this work, we used three principal techniques in the same samples. The first was based on the laser line orientation, the second focused on the orientation using a geological compass on the gypsum-planar and vertical surface, and the third was a simile to a paleomagnetic drill core of 3/8 inch diameter adapted to a geological compass.

The samples were cut lengthwise using orientations, for obtaining cubes of 15×15×15 mm. Each specimen was measured in a modified FIT Magnetometer to obtain the NRM. Samples are demagnetized applying alternating fields. We compare the results on a single stalagmite and discuss the effectiveness of sampling methods and their influence on paleomagnetic data.

## AS25-0768

# Magnetic boundary layer in non-slip geodynamo simulations with insulating mantle

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We investigate the boundary layer at the top of the Earth's core in non-slip geodynamo simulations for small values of the Ekman number, E≤10−6. Knowledge of this boundary layer is important since it acts as a filter between the time-evolving magnetic field in the core interior and the field at the core surface where models built from geomagnetic data are available, provided the mantle is electrically insulating. For the investigated low values of E, the boundary layer consists of a thin viscous sublayer of width √E and a thicker zone, where magnetic induction is compensated by diffusion. It ensures the transition between the magnetic field at the top of the free stream and a potential field at the core-mantle boundary and mainly affects the field's horizontal components. We show that its thickness δ scales as the skin depth for a magnetic field of time scale τ_SV/l, where τ_SV is the Secular Variation time scale and l is the spherical harmonic degree. Consequently, δ decreases with l and reaches its minimum, proportional to D/Rm (D depth of the fluid shell, Rm magnetic Reynolds number), for a value of l such that radial and horizontal diffusion are equivalent. Deep inside the core, the relative importance of magnetic diffusion is governed by the Elsasser number Λ, and diffusion vanishes in the limit Λ→∞. There is an intermediate region where the velocity and magnetic fields tend to be aligned to limit the strength of the electrical currents.

## AS25-0769

# Geomagnetic Variations Along the Southern Coast of Brazil Over the Past 50,000 Years

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The oceanic region near the southern coast of Brazil contributes minimally to the global geomagnetic database. This data gap may introduce inaccuracies in geomagnetic estimates produced by models for this region. A potential consequence is the misinterpretation of physical processes related to the geodynamo, which could hinder the understanding of geomagnetic variations observed in this area. In this study, we present inclination and pseudo-Thellier relative paleointensity data obtained from three ocean-floor sediment cores collected off the southern coast of Brazil, covering the Middle Holocene and Late Pleistocene. The average geographical coordinates of the cores are 29.3° S latitude and 47.2° W longitude. Age-depth models were constructed using radiocarbon dating, oxygen isotope tie points, and geomagnetic tie points. The cores have an effective length of 360 cm, with samples taken at 2.5 cm intervals, corresponding to an average temporal resolution of approximately 300 years per sample. Paleomagnetic analyses indicate that the primary magnetic carriers in the three sediment cores are pseudo-single-domain (vortex) magnetite. The inclination data exhibit low maximum angular deviations, and the mean inclinations are generally shallower than those predicted by the geocentric axial dipole model. The directional and intensity records show multisecular to millennial-scale oscillations, which, when compared with predictions from the GGF100k geomagnetic model, display similar variations. After refining age models, conducting quality assessments, and interpreting the data, these paleomagnetic findings can be incorporated into the global database, enhancing models of geomagnetic field evolution in the South Atlantic over the past 50,000 years.

## AS25-0779

# The history of geomagnetic secular variation hemispherical dichotomies

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Monitoring the geomagnetic field and its secular variation (SV) is essential for understanding Earth's internal dynamics. In particular, the SV provides an image of the geodynamo at the top of the core. However, the SV is not available for paleomagnetic field models. Here we propose a new index for assessing the paleomagnetic SV. This new index is based on the well-established inverse linear relationship between the SV timescales and the degree of spherical harmonics. We demonstrate using the historical field where the SV is available that this index adequately captures the large-scale features of the true SV, in particular the SV Atlantic/Pacific and North/South hemispherical dichotomies. The recovery of these SV dichotomies by our proposed index does not deteriorate from truncated fields at spherical harmonics degree 14 to 5. Applied to a paleomagnetic field model for the past 100 kyr, we find a persistent SV dichotomy between the quiet Pacific and active Atlantic hemispheres, consistent with heterogeneous inner core freezing. In addition, according to our index, a persistent stronger SV prevails at the northern hemisphere, which is the case at present day due to a fast westward jet at high latitudes of the northern hemisphere.

## AS25-0827

# Paleomagnetism and relative paleointensity variations during Cretaceous Normal Superchron in the Brazilian Equatorial Margin

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The early Cretaceous marks an important change in the Earth's magnetic field from a state of rapid polarity reversals, to one of long-term stability associated with the onset of the Cretaceous normal superchron (CNS) at ~121 Ma. Although it is a period of stability in the Earth's magnetic field, the CNS might have been characterized by more variability than previously thought. However, the current database is uneven in its spatial and temporal distribution. We have carried out a detailed paleomagnetic investigation of two stratigraphically overlapping sections from the Sergipe-Alagoas Basin, NE Brazilian margin, South Atlantic Ocean. Sampling was conducted over 183 m and 80 m intervals at SER-03 and SER-01 cores, respectively. Magnetic remanence and rock magnetic parameters, such as magnetic susceptibility ($\chi$), anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM), were measured. Rock magnetic analyses indicated that primary magnetizations were preserved throughout the interval, with detrital magnetite identified as the primary magnetic carrier, predominantly in the pseudo-single domain (PSD) and low-coercivity states. Normalizations by $\chi$, $ARM_{15mT}$ and $IRM_{15mT}$ were used to determine relative paleointensity curves and were compared to the curve resulting from the pseudo-Thellier method. The paleomagnetic record shows marked changes in both intensity and inclination. Inclination instability results are comparable with those found in volcanic rocks from surrounding the region. The high-resolution magnetic record revealed that the field variability was higher than expected during the CNS. The new data can serve as a dating and correlation tool for coeval records in this region.

## AS25-0835

# Axisymmetrisation of Magnetic Field within a Stably Stratified Layer in Mercury's Core

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Mercury's intrinsic magnetic field is very axisymmetric contrary to Cowling's theorem (1933). A stably stratified layer (SSL) has been introduced to reduce the non-axisymmetry of the field through ω-effect (e.g., Stevenson 1982) and/or attenuation by the skin effect (e.g., Christensen 2006).

To examine the role of the SSL against the Hermean intrinsic magnetic field, we adopted the dynamo model of Takahashi et al. (2019). The model was implemented a self-consistent spherical dynamo driven by doubly diffusive convection with the outer-most part being thermally stable.

We found the radial component of the magnetic field had strong axisymmetry in the shallower part of the SSL, though it remained non-axisymmetric in the convective layer. It was clear that different processes were on-going within the SSL compared with the convective region. According to the analysis of the magnetic Reynolds number, advection still had a greater effect on the magnetic field than diffusion in most of the SSL.

We then investigated how the axisymmetry of the magnetic field was strengthened within the SSL. We calculated the axial and non-axial magnetic intensities of the toroidal and poloidal fields as functions of radius, which showed a substantial decrease of non-axisymmetric poloidal field. By taking the ratio of axisymmetric poloidal intensity to that of non-axisymmetric poloidal field, it was found that axisymmetry of the poloidal magnetic field kept rising throughout the SSL to become as large as ～100. As for the toroidal field, the ratio showed no significant change.

## AS25-0877

# A secular variation model of Jupiter's magnetic field from Juno observations

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Jupiter's magnetic field is generated by the convection of metallic hydrogen within the planet. While the field is predominantly dipolar, it exhibits hemispheric asymmetries and regional anomalies, such as the "Great Blue Spot" (GBS), which has been suggested to undergo secular variation based on measurements from NASA's Juno mission. In this study, we analyze magnetometer data collected during Juno's first 62 perijoves, spanning from August 2016 to June 2024, to develop a secular variation model for Jupiter's main magnetic field. Our methodology involves a spherical harmonic expansion of the field in a Jupiter-fixed coordinate system, B-splines to interpolate the temporal variation of the internal field, and low-rank approximation to solve for the model parameters. The modeling results show improvements in data fit residuals when incorporating secular variation with optimized control parameters. During Juno's observation period, the dipole field strength decreased at a rate of approximately 0.06% per year, and the GBS continued to exhibit eastward motion. These findings provide new insights into the dynamic nature of Jupiter's magnetic field and its underlying processes.

## AS25-0881

# Thermochemical geodynamo models with core-mantle boundary heat flux variations

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In Earth's outer core, thermochemical convection driven by latent heat and light elements released from the freezing inner core powers the geomagnetic field. A key issue in core dynamics is the existence of a stable layer below the core-mantle boundary (CMB). Seismic velocity anomalies are often interpreted as evidence of an O(100 km) thick layer, while geomagnetic observations might reflect radial flow at the top of the core, which a stable layer would have suppressed.

In numerical geodynamo simulations with such a stable layer, the morphological semblance between simulated and observed fields tends to decrease with increasing layer thickness and strength of stratification. Recent simulations of convection and geodynamo, accounting for CMB heat flux variations, aim to reconcile these contradictory interpretations by proposing locally stable regions rather than global layers, while also producing Earth-like field morphology and secular variation. However, these simulations used a codensity approach that combines thermal and compositional anomalies and, therefore, ignores the vastly different thermal and chemical diffusivities and the different boundary conditions they can satisfy.

We have performed a suite of top-heavy "thermochemical" geodynamo simulations that include the differences in diffusivity and boundary conditions. Depending on the balance of thermal vs. chemical driving, the accumulation of hot and/or light element-enriched material below CMB in our models results in stable regions with varying locations, properties, and morphology. We characterize the stratification in our simulations and the geomagnetic signatures of these structures and compare them with observations of geomagnetic secular variation.

## AS25-0907

# Italian Magnetic Network and Geomagnetic field maps of Italy at year 2025.0

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For modelling the Earth's Magnetic Field (EMF) on a large scale, data from magnetic observatories, satellite missions, oceanographic campaigns and magnetic measurements at ground (magnetic campaigns or surveys) are generally used. The observation of the slow spatial and temporal changes of the EMF through the magnetic campaigns are carried out at regular time intervals, to characterize the magnetic behaviour of the outer terrestrial core. The measurements on a regional scale also allow defining the characteristics of the crustal component of the EMF generated above the mantle.

We show the results of the magnetic survey at 2025.0, which was executed from the end of 2024 to the beginning of 2025. The need to optimize the network led to a revision of the total number of stations, settling the current configuration to around 40 measurement points, integrated with the 4 geomagnetic observatories and 2 variometric stations over the Italian territory. The characteristics of the Italian Magnetic Network and of the measurements are described. The results of the survey, obtained after reduction procedures to the common epoch 2025.0, include the maps of the different magnetic elements of the magnetic field (D, H, Z components and total field F) over Italy, as well of their time variation.

## AS25-1038

# Axial dipole decay during excursional events in numerical dynamo simulations

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Geomagnetic excursions are extreme variations in the Earth's magnetic field that have been found to be characterized by anomalous directional and intensity changes in the field, without undergoing a full polarity switch in the manner of a reversal. Paleomagnetic studies have shown that such intensity changes are associated with a reduction in the field contribution from the axial dipole component, whilst equatorial dipole and non-dipole components remain largely unaffected. This feature of excursional events has been reproduced in numerical dynamo simulations ran in a computationally accessible parameter space for paleomagnetic timescales. Simulations have the advantage of generating velocity and magnetic field throughout the core, allowing the mechanism behind the decrease in axial dipole moment during excursions to be directly explored. We will present results from geodynamo simulations in which we associate axial dipole decay with contributions from magnetic diffusion and advection. We find that decreases in the axial dipole moment are linked to the advection of opposite polarity flux patches across the core surface to the poles. We will analyze how regions of magnetic flux are transported through the core to its surface, enabling us to explore where geomagnetic excursions originate and the physical processes occurring in the core during such events.

## AS25-1168

# Reconstructing the past geomagnetic field's variation in Asia as a tool for archeomagnetic dating

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The large number of archeomagnetic studies, which were conducted since the early 60s on archeological artifacts from Asia, can provide valuable insights into the past behavior of Earth's magnetic field within this continent. Taking advantage of this comprehensive and well-distributed dataset, this study presents a first regional reconstruction of the ancient geomagnetic field variation in Asia, covering the past four millennia.

This paleoreconstruction incorporates both data from well-dated archeological baked clay structures and artifacts, as well as data from volcanic eruptions of known date, included within the target geographical area and chronological timeframe. Prior to modeling, a meticulous data selection process has been applied to establish a robust weighting scheme, in order to enhance the quality of the data and thus the accuracy of the modeling approach. Furthermore, historical data from the HISTMAG compilation have been integrated to further refine our comprehension of the geomagnetic field's behavior over the last few centuries.

The regional Asian paleoreconstruction employs R-SCHA2D functions in spatial dimensions and cubic splines in the temporal domain. The study region is defined within a 50° spherical cap centered at the coordinates 35.0ºN, 102.5ºE. This model not only advances our capacity to better characterize the past behavior of the Earth's magnetic field in Asia but also enables the generation of new paleosecular variation curves that can be used as reference curves for archeomagnetic dating. Using these curves, dating precision has been assessed for the past millennia within the Asian continent.

## AS25-1218

# Core-surface flows during the last 3300 years

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Understanding the Earth's magnetic field evolution requires examining the fluid flow at the core-mantle boundary that drives the changes over different timescales. The inversion process to derive core-surface flow velocities from secular variation data encounters non-uniqueness issues, necessitating a priori assumptions that yield different flow solutions. In this work, we investigate the Earth's core-surface flows over the last 3300 years using an archaeomagnetic model to invert for time-dependent purely toroidal and tangentially geostrophic solutions. We apply the constraints as regularization terms that let us reproduce different large-scale flows at the outer core surface. We evaluate the frozen flux hypothesis and we show that the temporal averaging range in archaeomagnetic models reliably captures the long-term behavior of core-surface flows over time. Then, we use these core-flow models to analyze different global phenomena, as the robust episodes of large-scale eastward and westward flow and the exchange of angular momentum that contributes to the Length of the Day variations at millennial time-scales.

## AS25-1223

# A new quality-weighted global geomagnetic field model for the last 5k years

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Understanding the past behaviour of the Earth's magnetic field is fundamental to deciphering the dynamics of our planet's interior. Palaeomagnetic records provide the information on both the direction and intensity of the field as preserved in sedimentary sequences, lava flows, and heated archaeological materials. Continuous efforts by the paleomagnetic community to increase the high-quality datasets necessitate regular updates to existing geomagnetic field models. In this study, we present a new global reconstruction for the last five millennia based on thermoremanent acquired data from volcanic and archaeological materials. We have revised and updated the GEOMAGIA database to incorporate newly published data from 2020 to 2024. Our modelling approach applies a weighting scheme based on the quality of laboratory protocols and the number of specimens per sample, following the criteria used in previously published models (SHAWQ2k and SHAWQ-Iron Age). We use spherical harmonic analysis in space and cubic B-splines in time, incorporating spatial and temporal regularization to minimize the geomagnetic field's energy at the core-mantle boundary. For the first time, we implement time-dependent damping parameters to account for the sharp decline in data availability beyond the turn of the era and analyse the impact in the final reconstruction

## AS25-1272

# Global study of geomagnetic secular variations and jerks: Utilizing satellite data and comparative analysis with geomagnetic models

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Secular Variations refer to long-term changes in the Earth's magnetic field that occur over timescales of decades to centuries. These variations are distinct from short-term fluctuations such as daily or annual changes. Secular variations are significant because they provide insights into the dynamic processes occurring in the Earth's outer core, where the magnetic field is generated. The variations are driven by the geodynamo process, which involves the movement of molten iron in the Earth's outer core. These movements generate and sustain the Earth's magnetic field. Studies of secular variations reveal changes in the intensity and distribution of the magnetic field. For instance, the Earth's magnetic field has experienced periods of increased or decreased strength. Understanding the occurrence of secular variations and jerks helps in interpreting the Earth's magnetic history and contributes to models of core dynamics. It also has practical implications for navigation systems and understanding the impact of the magnetic field on technology. The study intends to utilize satellite data and comparative analysis with geomagnetic models with data from ground observatories to understand the global nature of secular variations and jerks.

## AS25-1276

# Understanding the Late Glacial and Holocene geomagnetic variations from sediments in Eastern Central Europe: Current knowledge, challenges, and future directions

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Investigating regional variations in past geomagnetic field behavior is crucial for understanding the evolution of the Earth's magnetic field. Sedimentary records serve as valuable archives for studying these changes, including both dipolar and non-dipolar field components. Recent global paleomagnetic data compilations reveal distinct regional differences in geomagnetic field behavior, with Europe being among the regions with the most pronounced geomagnetic variations. However, the scarcity of sedimentary paleomagnetic data for 0–15 ka BP in Eastern Central Europe limits our understanding of geomagnetic variations at regional scales. Additionally, projections based on current geomagnetic models indicate attenuated paleomagnetic signals, greater ambiguities, and significant discrepancies beyond 8 ka BP in this region. The lack of data also restricts the potential for paleomagnetic dating in terms of geochronology and limits regional insights into past environmental changes. These constraints underscore the need for improved data coverage through high-quality sedimentary paleomagnetic records with high-resolution and robust age control for regional field reconstructions, which in turn enhance global geomagnetic field and secular variation models. Here, we present the current state of knowledge, key challenges, and opportunities for studying geomagnetic field behavior in Eastern Central Europe, with a focus on the extent to which paleomagnetic records are modulated by the impact of past climatic changes.

## AS25-1328

# Archaeomagnetic results from Sierra Boyera archaeological site (Iron Age, southern Spain)

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An archaeomagnetic study was performed on a kiln situated in Sierra Boyera'sOppidum, Córdoba (Spain). The kiln's last use (IV–III BCE) was inferred fromthe appearance of an Iberian amphorae linked to the collapse of the grill. Thesite's chronology is estimated to be from IV to II BCE. An archaeomagneticsampling was carried out in order to get new data for Iberia in this timeframeand to evaluate the archaeomagnetic dating technique. Two sets of specimenswere picked to be demagnetized by: alternating-field demagnetization (AF) andThellier-Thellier experiments, including partial thermoremanent magnetizationchecks (pTRM-checks) and magnetic anisotropy measurements with the goal ofcorrecting its effect on thermoremanent magnetization. Once thepaleodirections and paleointensities of the samples were obtained, Fisherdistribution was used to calculate the standard paleomagnetism parameters. The kiln's resulting mean direction was: inclination 60.0°, declination -3.3° andstatistical parameters = 2.2° and k = 240.4; and mean paleointensity was 70.3 ± 3.4 μT. Considering the archaeological context and using the Iberia – IronAge's paleosecular variation curve, the dating intervals for the last use of thekiln are 435–390 BCE and 310–265 BCE. This result was reached by verifyingthe consistency between the archaeomagnetic dating and the archaeologicalinformation.

## AS25-1456

# Utilizing codensity approach to assess how core-mantle boundary properties influence geomagnetic reversal frequency

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Over the past decade, advances in data assimilation techniques combined with a rapid increase in computational power have allowed for increasingly realistic dynamo simulations. One of the key parameters controlling the dynamics of the magnetic field is the amount of heat loss through the core-mantle boundary (CMB), highlighting the crucial role of the lower mantle in the dynamo processes. Previous studies (Kutzner and Christensen, 2004) suggest that heat flux variations at the lower mantle may explain the observed changes in reversal frequency on time scales of some 10 million years.

To study the effect of the mantle on reversals, we use the numerical code MagIC, simulating the dynamo process over geological timescales. The long required simulation time forces us to use a relatively large Ekman number of E = 3e−4. Following Frasson et al. (2024), we first explore the impact of several fundamental heat-flux patterns (spherical harmonic degree Y10, Y20, Y22, …) and amplitudes imposed at the outer boundary. Secondly, we use a codensity approach to explore whether a higher degree of compositional driving reduces the impact of the core-mantle boundary heat flux pattern. Finally, we investigate the impact of the stably stratified layer at the top of the outer core (Buffett et al., 2016) on the geodynamo process and the stability of the magnetic field.

By combining these approaches, we enhance the complexity of the geodynamo model to better capture Earth-like geomagnetic field variations (Olson et al., 2013).

## A04 Modelling, ground and space-based data and innovations for the geomagnetic main field: IGRF-14 generation and the future

### AS25-0042

# Broadband a priori temporal cross-covariances for the geomagnetic inverse problem: application to the satellite era

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We present COV-SAT, a magnetic field model covering the era of continuous satellite monitoring from space, constrained by ground-based and virtual observatory data. It incorporates as a priori information temporal cross-covariances associated with auto-regressive processes of order 3. These are derived analytically, and rely on a small number of free parameters (variances and time-scales) deduced from spectral properties extracted from long magnetic records and geodynamo simulations. The new a priori information proposed here encompasses power spectra stemming from paleomagnetic, observatory and satellite records, statistically replicating magnetic variations over a broad range of time-scales. It furthermore allows the cut-off in the spectral density expected for periods shorter than about 2 years, the Alfvén time in Earth's core, to be mimicked. Field model coefficients are projected in time based on the a priori cross-correlation functions, avoiding the use of arbitrary temporal basis functions. This formalism is exploited to forecast the field evolution, and to provide uncertainties for the estimated main field and its secular variation over the upcoming 5 years.

## AS25-0106

# MISTA candidate magnetic field models for IGRF-14

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The International Geomagnetic Reference Field (IGRF) is a mathematical model representing the large-scale Earth's main magnetic field. In 2024, the International Association of Geomagnetism and Aeronomy (IAGA) V-MOD Working Group called for candidate models for the 14th generation of IGRF (IGRF-14). In response, the Macau Institute of Space Technology and Application (MISTA) submitted three candidate models: the DGRF-2020 model for the main field at epoch 2020.0, the IGRF-2025 model for the main field at epoch 2025.0, and the SV-2025–2030 average secular variation (SV) model for 2025.0–2030.0. These models were derived using a new framework that simultaneously determines Earth's magnetic field and mantle conductivity. Data from the Macau Science Satellite-1 (MSS-1), the Swarm satellite, and global observatories were integrated for model construction. This study describes the methodology used to derive our candidate models and their validation.

## AS25-0183

# The CHAOS-8 geomagnetic field model and derived IGRF-14 candidates

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The CHAOS-8 model describes the time-dependent near-Earth geomagnetic field between 1999 and 2025 and is the latest update of the CHAOS modeling series. It is derived from magnetic field observations collected by the low-Earth orbit satellites Swarm, MSS-1, CSES, CryoSat-2, CHAMP, SAC-C, Ørsted, and from annual differences of monthly means of ground observatory measurements.

The model consists of a time-dependent internal field up to spherical harmonic degree 20, a static internal field that merges to the LCS-1 lithospheric field model above degree 25, a model of the magnetospheric field and its induced counterpart, estimates of Euler angles describing the alignment of satellite vector magnetometers, and magnetometer calibration parameters for CryoSat-2. CHAOS-8 also includes a climatological model of the ionospheric E-layer magnetic field for the first time in the CHAOS model series. In addition, the temporal regularization of the internal field is now based on the expected physical processes in Earth's core via temporal covariances extracted from geodynamo simulations that include realistic rapid core dynamics.

The talk presents the CHAOS-8 geomagnetic field model and discusses the improvements compared to the previous version, CHAOS-7. In addition, it reports on the construction of the candidate models using CHAOS-8, which were submitted as contributions to the most recent generation of the International Geomagnetic Reference Field (IGRF-14).

## AS25-0191

# Global main magnetic field modeling and secular variation analysis based on multi-satellite observations

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In this study, we utilized vector and scalar magnetic measurements from four Low-Earth Orbit satellites, the ESA's Swarm A and B, GRACE Follow-On and CryoSat missions. Data considered are from January 2019 to July 2024. By employing spherical harmonic analysis combined with a multi-source joint inversion approach, we constructed a global main magnetic field model, namely WHU-EMM01. The internal spherical harmonic coefficients of this model are truncated at degree 15 (with the potential to extend to degree 40 to describe the lithospheric field). The temporal variations of the main field are represented by 6$^{th}$-order B-spline functions (with a six-month knot interval and quintuple knots at the boundaries), enabling accurate estimation of both the secular variation and secular acceleration of the main field.

To investigate the impact of various satellite data on the inversion results, we conducted six sets of control experiments using identical regularization parameters and B-spline knot settings. The findings indicate that integrating a greater variety of satellite observations, including the non-dedicated magnetic mission like GRACE-FO and CryoSat, yields a more stable secular acceleration field modelling. In the model evaluation, we compared WHU-EMM01 with the comprehensive field model CHAOS-7 (Finlay et al., 2020) and IGRF-13 in terms of power spectra and global distributions of main field components. The results show that the average difference between WHU-EMM01 model and CHAOS-7/IGRF-13are less than 10 nT. Furthermore, the evolution of the main magnetic field from 2019 to 2024 agrees also quite well between our model and the others.

## AS25-0382

# Local Flow Estimation at the top of the Earth's Core using Physics Informed Neural Networks

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The Earth's geomagnetic field arises from the motion of liquid iron in the fluid outer core. By assuming that magnetic field changes are advection-dominated, the motion of fluid at the core surface can be related to the changes of the geomagnetic field, providing an observational approach to understanding the dynamics in the outer core. Most core flow models are described by global basis functions such as spherical harmonics, in which any point on the CMB depends non-locally on all the points in the model. In a local flow inversion, the same point should only depend on the other points in the region, allowing for a more detailed study of regional features without uncertainty from neighbouring regions.

This work introduces a novel technique based on Physics-Informed Neural Networks, to perform local flow inversions. Our approach seeks to minimise a loss function incorporating both data loss (fitting magnetic field variations) and a physics-based loss (ensuring the flow satisfies a given dynamical condition). We present the neural network set-up and results using the tangentially geostrophic flow constraint, but other dynamical assumptions can be accommodated. Our methodology does not suffer from leakage between regions, and we reproduce flow features seen in other global studies, such as the anticyclonic planetary gyre, showing that this is a data-driven feature not reliant on the details of any specific inversion method. We summarise our candidate SV model for IGRF-14 based on advection of the main field by a steady global flow, built from a mosaic of regional models.

## AS25-0491

# Allowing for geomagnetic jerks in the IGRF-14 Edinburgh candidate model for secular variation

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The International Geomagnetic Reference Field (IGRF) has been regularly updated since its inception in 1965. Every recent iteration contains an estimate of the geomagnetic secular variation (SV), for the intermediate years between iterations. We submit a candidate model for the geomagnetic secular variation (SV) for the period 2025–2030 for the 14$^{th}$ generation of the IGRF. Our SV prediction is based on the inferred periodic behaviour of core-surface flow acceleration. The reasoning for this is based on recent evidence for core waves, the existence of which justifies using periodic behaviour of core-surface flow acceleration.

We obtain a core-surface flow model, in terms of poloidal and toroidal flow coefficients, from spatial gradients of SV data from Swarm from 2014–2024, and calculate the flow acceleration from the first time-derivative of these coefficients. This is done without relying on numerical simulations for prior information, band-pass filtering or enforcing any flow geometry (such as quasi-geostrophy). We fit each acceleration coefficient with a sinusoidal function, which is used to extend their time series until 2030. We then obtain the core flow coefficients through integration over time, and from the core flow we calculate the average predicted SV over the five-year IGRF period.

Our model predicts moderate geomagnetic jerks in 2024 in the Equatorial Pacific, and in 2027 in the equatorial Atlantic. Although the IGRF SV prediction is a snapshot over a 5-year period, allowing for periodic behaviour offers potential improvements over the usual linear prediction.

## AS25-0518

# Do ground-based magnetic observatories provide sufficient magnetic field measurements to construct a model that meets the IGRF specifications?

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The IGRF model requires global measurements to accurately represent the Earth's magnetic field across all latitudes and longitudes. Ground-based observatories are fixed at specific locations on the Earth's surface. While these observatories play a crucial role in providing accurate and continuous data—essential for monitoring geomagnetic disturbances—their spatial coverage is limited, especially in remote and high-latitude areas and large parts of the oceans.

In this presentation, we propose estimating an IGRF-like candidate model (for the IGRF and secular variation part) using only magnetic observatory data. To do this, we utilize the open INTERMAGNET database to first estimate the maximum spatial resolution achievable from this dataset in spherical harmonics. We show that, without any prior information, the static internal part of the field can be represented with reasonable confidence up to spherical harmonic degree 6 to 8, depending on the considered epoch. However, by incorporating simple prior information at the core-mantle boundary, one more pertinent magnetic field model could be estimated up to spherical harmonic degree 12. While this model does not fully meet the specifications of typical IGRF candidate models derived from a combination of ground-based and satellite data, its static component achieves a resolution comparable to that of the World Magnetic Model. Finally, we design a Bayesian process to numerically explore different combinations of weights applied to observatory measurements in space to investigate the possibility of further improvements and we probabilistically highlight geographic regions where ground-based observations are critically lacking for the purpose of main field modelling.

## AS25-0543

# Short-term secular variation seen in decadal magnetic field models

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We compute magnetic field models from mostly ground-based geomagnetic observations over the period 1956 to 2025. Our modeling strategy employs secular variation estimates derived from annual differences of observatories monthly means. The resulting models are compared to a recent satellite-based geomagnetic field model (Chaos 7.16) that covers the entire satellite era from 2000 to 2025. Both models use order 6 B-splines, which provides robust results for the secular acceleration. While the core field descriptions of the two models highly agree (correlation $\sim$0.92 at spherical harmonic degree l = 14), the both descriptions of the secular variation deviates, most noticeable on intermediate length scale. This difference may be explained by the difference of source geometries within satellite and ground-based data sets. Satellite data consider every magnetic field generation below their orbital sphere to be of internal origin. However, this might be difficult as night-time and quiet-time ionospheric field generation may also map into these data as internal sources. An indication for this might be the higher power of ground-based secular variation models for spherical harmonic degrees l = 4–12. We also devise a way to derive temporally more detailed secular variation estimates. Here, we aim to identify short-term secular variation most vivid in the equatorial region and the imprint of a quasi-biennial variation that possibly originate in the ionosphere and/magnetosphere. The presented model was used to deduce candidates for the different IGRF-14 derivatives (definitive field model for 2020, current field model for 2025, secular variation forecast for 2025–2030).

## AS25-0603

# Observatory-based geomagnetic field modelling for the post-Swarm era

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Before the space age, geomagnetic field models used only data from ground-based observations. In the decades since 1999, satellite data have become increasingly dominant for such modelling as they provide a near-global coverage that observatories or other ground surveys can never achieve. However, satellites have lifespans limited by fuel supply and environmental conditions. The ESA Swarm mission is expected to end before the mid-2030s for example. Whether for calibrating the next generation of cube-satellite missions or bridging a gap in time before new polar-orbiting vector magnetometer missions, magnetic observatory data remain a vital dataset for capturing secular variation.

We present a family of models using only observatory data (though with satellite-derived observatory biases). These models achieve a root-mean-square vector magnitude difference over Earth's surface of around 70 nT when compared to the core field of an established reference satellite-based model. The data selection, model inversion and plotting of results can be achieved in under 30 seconds on a modern laptop, illustrating the great computational efficiency of using only a low volume of observatory data. By using expected geomagnetic power spectra and the properties of Legendre functions, we also produce a prior covariance matrix between the unmodelled magnetic field contribution of all data points used. This comes at greater computational expense, but it allows a better understanding of the errors in the model coefficients inherent from the uneven spatial distribution of the observatory network.

## AS25-0605

# The ESA Scout NanoMagSat mission and beyond, towards improved permanent geomagnetic field and ionospheric environment monitoring and modeling

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Since the launch of the ESA Swarm constellation, substantial international efforts have been made to further enhance our capacity to monitor and investigate the geomagnetic field and ionospheric environment.

NanoMagSat is the ESA EO effort in this direction, specifically designed to further improve temporal resolution of geomagnetic and ionospheric observations. It will consist in a new constellation of three 16U Cubesats carrying miniaturized instruments, including one low frequency absolute vector magnetometer with two star-trackers, one high frequency vector magnetometer, a multi-needle Langmuir probe and GNSS receivers for orbit determination and ionospheric radio-occultation. The deployment of the constellation into two inclined (~ 60°) orbits with appropriate delta RAAN and one polar orbit at an initial altitude of 545 km will provide an innovative solution for fast local time coverage, beneficial to investigate fast planetary magnetic signals.

NanoMagSat is being developed within the new ESA EO Scout framework, exploiting the New Space paradigm to quickly deliver innovative Earth Science missions within a budget of 35M€ and a schedule of three years from mission kick-off to launch. It currently is in Phase B and will start deploying end of 2027. The full constellation will be operated for at least three years between 2028 and 2031, possibly overlapping with the Swarm, CSES and MSS-1 missions.

The rationale for the choice of the payload and constellation design will be presented, together with the planned data products. The opportunity of building on the NanoMagSat low-cost approach for maintaining permanent international space-born observations will also be discussed.

## AS25-0620

# A DGRF 2020 candidate model based on Swarm ASM experimental vector mode data improved through a dedicated post-calibration strategy

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ESA Swarm satellites carry a magnetometry payload consisting of an absolute scalar magnetometer (ASM), a fluxgate vector magnetometer (VFM), and a set of star trackers (STR). The primary role of the ASM is to provide 1 Hz absolute field intensity measurements, while the VFM and STR provide the additional data needed to reconstruct the attitude of the vector field to produce the official nominal Swarm L1b magnetic data. Each ASM instrument, however, can also produce its own self-calibrated 1 Hz experimental vector data, or, when requested, 250 Hz scalar burst data. Self-calibrated 1 Hz experimental vector data have routinely been produced ever since launch when the ASM instruments were not in burst mode. These data have been used to produce the only DGRF 2020 candidate model only relying on such data. All other candidate models relied on either nominal Swarm L1b, or data from other satellites and ground observatories.

Here we will report on the way this DGRF candidate model was built, and on the post-calibration strategy that we used to further improve the quality of this model, only and entirely relying on a dedicated analysis of model residual signals. Our final candidate model turns out to be one of the DGRF 2020 candidate models closest to the final official DGRF model, a posteriori providing evidence of both the quality of the Swarm ASM experimental vector mode data and the value of our post-calibration strategy.

## AS25-0629

# Swarm and Friends—towards a fleet of satellites for exploring Earth's magnetic field

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Magnetic data from the Macau Science Satellite MSS-1 (launched in May 2023) combined with data from the Swarm satellite trio (in orbit since November 2013) enables an improved separation of the various contributions to Earth's magnetic field. In addition, and despite their lower data quality, calibrated magnetic measurements from so-called "platform magnetometers" onboard satellites like CryoSat-2, GRACE and GRACE-FO further enhance the space-time sampling of magnetic observations, allowing for new opportunities for studying both rapid core field variations at low latitudes and the local-time dependence of large-scale magnetospheric current systems.

In this presentation, I'll describe the complementary nature of polar-orbiting (Swarm) and low-inclination (MSS-1) satellites for geomagnetic field modelling and the possible improvements by combining the various datasets.

## AS25-0773

# Geomagnetic Secular Variation Prediction Using Recurrent Neural Networks trained by the Kalman filter: A Data-Driven Approach for IGRF-14

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This study introduces a machine-learning-based approach to predict geomagnetic secular variation (SV) using an EKF-RNN model, combining a Recurrent Neural Network (RNN) with the extended Kalman filter (EKF). The International Geomagnetic Reference Field (IGRF), updated every five years, provides a standardized description of Earth's magnetic field, including five-year linear SV forecasts. Traditional forecasting methods rely on computationally expensive geodynamo simulations, which struggle to capture sudden nonlinear changes such as geomagnetic jerks.

The EKF-RNN framework leverages RNNs' strength in modeling temporal sequences while incorporating EKF's efficient data assimilation technique. By dynamically updating RNN weights using error covariance from training data, the EKF mitigates overfitting and enhances learning efficiency. This approach offers a computationally lightweight alternative to traditional methods.

To assess performance, we conducted five-year hindcast experiments for epochs spanning 2004.50 to 2014.62, using geomagnetic field data from observatory hourly means, CHAMP, and Swarm-A satellite measurements (MCM model). The EKF-RNN model achieved forecast errors below 85 nT, outperforming traditional data assimilation methods such as 4dEnVar. Furthermore, the EKF-RNN framework provided forecast error covariance matrices, enhancing interpretability and robustness.

These results suggest that the EKF-RNN model is a promising alternative for predicting geomagnetic SV, improving the accuracy and reliability of IGRF updates. This approach marks a significant advancement in data-driven geomagnetic field modeling, addressing computational challenges while achieving superior predictive performance.

## AS25-0825

# IGRF-14: evaluation of candidates and the construction of the final model

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In November 2024, the 14th revision of the International Geomagnetic Reference Field (IGRF) was issued by the International Association of Geomagnetism and Aeronomy (IAGA) Division V Working Group (V-MOD). This revision comprises two new spherical harmonic main field models for epochs 2020.0 (DGRF-2020) and 2025.0 (IGRF-2025) and a model of the predicted secular variation for the interval 2025.0–2030.0 (SV-2025–2030), all provided as Gauss coefficients to degree and order 13 for the main field or degree and order 8 for secular variation. The models were produced from candidates submitted by nineteen international teams. The candidate models were evaluated by a volunteer Taskforce and comparisons between all candidates as well the mean, median and a robust Huber-weighting of all candidates were made using well-established statistical criteria. These analyses were used to identify, for example, the variation between Gauss coefficients or geographical regions where the candidate models strongly differed. The majority of candidates were sufficiently close that the differences can be explained primarily by individual modelling methodologies and data selection strategies. Indeed, none of the candidates were sufficiently different to warrant their exclusion. The IAGA V-MOD task force thus voted for two approaches: the median of the Gauss coefficients of the candidates for the DGRF-2020 and the computed robust Huber mean in space for the IGRF-2025 and SV-2025–2030 models. We describe the evaluation of the candidate models and provide details of the approach used to derive the final IGRF-14 products.

## AS25-0872

# Uncertainty Quantification for Core Field Models Derived from Ground Observatory Data

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The Earth's magnetic field is a superposition of the core field, crustal field and external disturbance fields originating from the ionosphere and magnetosphere. The core field is mostly described by spherical harmonic coefficients up to degree and order 15, and this component of the magnetic field changes slowly on the order of years. Core field models such as the IGRF and WMM are produced every five years to capture changes in the field using magnetic measurements from spacecraft in low-Earth orbit. This study explores core field models developed exclusively from ground-based magnetic observatories, where incomplete spatial sampling leads to partial unobservability of the model parameters. At NCEI, we use ground-based models as a reference for spacecraft magnetometer calibration in support of the WMM. In this study, we develop synthetic gauss coefficients based on the characteristics of the core field over the past 25 years to generate potential future Gauss coefficients, and then use these synthetic future realizations to evaluate the uncertainty in models derived from various sets of fixed ground observatories. We also compare an empirical inversion scheme to standard regularization techniques that are typically applied to core field models. Finally, we explore potential locations for new ground observatories to reduce the global uncertainty.

## AS25-0889

# The UCM contribution to IGRF-14

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The 14th generation of the International Geomagnetic Reference Field (IGRF-14) was released at the end of 2024. Here, we present an overview of the contributions made to its development by the Spanish team led by the Universidad Complutense de Madrid (UCM). Our team presented candidate models for all three required products: the definitive geomagnetic reference field for epoch 2020.0 (DGRF2020), the main field model for epoch 2025.0 (IGRF2025), and the predictive secular variation model for 2025–2030 (SV2025–30). These models were constructed using satellite data from the Swarm mission and ground-based geomagnetic observatories. Our methodology involved the development of two parent models covering the periods July 2019 to July 2020 and September 2023 to September 2024, incorporating contributions from the core, lithospheric, external and induced fields. A bootstrap ensemble approach was used to estimate uncertainties and ensure the robustness of the final models. In this work we present a retrospective analysis comparing our candidate models with the final IGRF-14 model, as well as with our previous contributions to IGRF-13, highlighting the progress and improvements made in the development of the candidate models for this new generation.

## AS25-0906

# Satellite Observations of Magnetic Signals due to Ocean Dynamics

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The movement of the ocean through Earth's main magnetic field induces electrical currents. These electrical currents, and their closure in the solid Earth, result in Ocean-Induced-Magnetic Fields (OIMF) that carry integrated information on the ocean flow, its dynamics, and its electrical conductivity that in turn depends on the ocean's temperature and salinity. OIMF signals for a number of ocean tidal components have been convincingly isolated in satellite observations but detection of the OIMF signal due to the general circulation of the ocean and its dynamics has remained elusive. In this contribution we present the results of our recent efforts to detect the OIMF signal due to ocean dynamics using observations made by the Swarm satellite trio. This involves (i) a scheme to correct as best as possible for other geomagnetic signals (from the core, crust, ionosphere and magnetosphere), (ii) time-dependent field modelling with a focus on spherical harmonic degrees 15 to 30 and periods of 60 days up to 5 years and model regularization suitable for studying the OIFM (iii) post-processing to highlight the OIMF signal. We will presents results of experiments carried out with synthetic satellite data based on simulated ocean signals and with real Swarm satellite observations with a focus on regions such as the Indian Ocean where strong OIMF signals are expected.

## AS25-0948

# Recent IGRF versions and global models: fate and features

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Forecasting the International Geomagnetic Reference Field (IGRF) model based on geomagnetic field observation from various satellites and ground magnetic observatories, given the accuracy needed for an SV model, turned out to be notoriously challenging.

A joint approach is taken by the HZDR (Helmholtz-Zentrum Dresden-Rossendorf) and the GFZ (Helmholtz-Centre for Geosciences) to investigate the geomagnetic field predictability on both, short and long time scales and to combine (in project GEOMAGFOR) the complementary expertise of the two groups from the observational and empirical modelling side at GFZ and the theoretical and experimental side at HZDR.

Here we present as a first step from the observational side a comparison of recent IGRF contributions, to identify the updates made on the SV predictions by IGRF, and DGRF versions and also to compare it with the behaviour for some continuous models (CHAOS and Mag.num). In particular we focus the analysis on the first coefficients of the spherical harmonic analysis (SHA), compare it with own (simple) auto-regressive (AR) and now classic deep learning (DL) forecast experiments, both on the SHA coefficient time series itself and derived more physical dipole parameters (using LSTM and GRU approaches) by looking for all at the effect on real Earth features like the South Atlantic Anomaly or the approximating eccentric dipole.

## AS25-0975

# Geomagnetic Virtual Observatories from the Macau Science Satellite mission

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Geomagnetic Virtual Observatories (GVOs) are a method for processing satellite data to simulate observations of the geomagnetic field at a static location, and to derive secular variation timeseries akin to those from ground observatories. Data are collected in a volume of space over a period of time and reduced, via fitting to a local potential field, to a point estimate. Geomagnetic satellites in polar orbits typically drift through all local times over a period of months to years, and a GVO sampling period shorter than this local time precession period produces a biased sampling of, for example, the ionospheric field, which contaminates the data.

The Macau Science Satellite (MSS-1A) was launched in May 2023 into a 41° inclined orbit, and precesses through all local times in roughly 26 days, compared to the roughly 133 days of the ESA Swarm mission. MSS-1A provides a unique data source capable of supporting higher time resolution GVOs, within roughly a band of ±40° latitude.

With the first year of MSS-1A data now available, we perform an initial investigation of GVOs, testing the suitability of the methodology developed for Swarm data, and the content of the resulting GVOs data series.

Initial GVOs results show a good correlation between MSS and Swarm GVOs timeseries, and that GVOs series can be robustly produced at a higher time sampling than for Swarm with MSS-1A data. Even with the limited time span of data available, we investigate the secular variation captured by MSS GVOs.

## AS25-0977

# The BGS IGRF-14 candidate models and evaluation of IGRF-13 secular variation predictions

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The International Geomagnetic Reference Field (IGRF) is a model of the Earth's internal magnetic field updated every five years via a call to the scientific community for candidates at fixed periods in time. We present the three BGS candidate models submitted to the 14th generation call in late-2024: (i) a definitive model for 2020.0, (ii) a prospective model for 2025.0, and (iii) a secular variation prediction for the period covering 2025 to 2030 based on steady-acceleration core surface flows. The candidates were derived from a combination of ground observatory, ESA Swarm and Macau Science Satellite (MSS-1A) data. We find the MSS-1A data to be of comparable quality to that of Swarm, to the benefit of producing accurate global field models. We also retrospectively assess the performance of the seventeen secular variation candidate models submitted for IGRF-13 in late-2019. We compare candidates to the retrospective IGRF-14, and ground and geomagnetic virtual observatory data, for 2020 to 2025, to comment on the state of secular variation prediction capability given the array of physics-based and analytical prediction methods used.

## AS25-1021

# A model of the magnetic field generated in the magnetosphere derived from ground observatory data

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The geomagnetic field observed at the Earth's surface or at satellite altitudes is the result of a combination of signals generated by both internal and external sources. Internal sources include magnetic fields produced by the geodynamo in the Earth's outer core, as well as fields generated by magnetized rocks in the lithosphere and induced magnetic fields within the lithosphere and mantle. External sources of the magnetic field are located in the ionosphere and magnetosphere, and are driven by electric currents. In this presentation, we outline an approach to extract and model the magnetospheric field contributions using magnetic observatory vector measurements. These data have a high temporal resolution and are particularly well-suited to characterize magnetospheric signals in space over a wide range of time scales. The goal of this work is to reliably characterize these signals from 1996 to 2024, during geomagnetically quiet times, spatially up to spherical harmonic degree 6, with a temporal resolution in time of one hour. For this, we apply an approach that uses a combination of the Kalman filter and correlation-based techniques. This method offers a more robust statistical framework, providing more accurate error estimates for the model parameters. We evaluate the model's key features using standard criteria, such as fit to the data, posteriori model distribution, shapes of power spectra over time, spatiotemporal geographical variations and correlations with geomagnetic indices like the Dst and RC indices. A Fourier analysis of the models shows the expected semi-annual, monthly, and daily harmonics, as well as tidal signals.

## AS25-1119

# Characterizing Altitude and Geomagnetic Activity Influences on Errors in Global Geomagnetic Model

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Global geomagnetic models, such as the World Magnetic Model (WMM) and International Geomagnetic Reference Field (IGRF), are used for navigation and space applications, yet their accuracy at altitudes beyond ground level remains underexplored. This study quantifies WMM errors from Earth's surface to 10,000 km, integrating contributions from crustal, ionospheric, and magnetospheric fields using a multi-model framework (T89 magnetospheric, EMM crustal, AMPS/DIFI ionospheric) and validating results with in-situ satellite data (Swarm, CryoSat-2, Ørsted). We find that errors in magnetic components (X, Y, Z, H, F) decrease with altitude due to reduced crustal field influence, with relative errors minimized near 400 km. Under quiet to moderate geomagnetic conditions (G0–G1, 85% of days), the WMM remains within Military Specification (MilSpec) accuracy limits of up to ~1,000 km. However, heightened geomagnetic activity (G2+) significantly reduces model validity, particularly for X, F, and H components, which exhibit greater sensitivity to external fields. Satellite data confirm these altitude-dependent trends. The study advocates for geomagnetic activity-dependent error metrics, for both scientific and operational users in an era of expanding space-based applications.

## AS25-1365

# GCRAS candidate field model for IGRF-14

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We present candidate geomagnetic field models developed for submission to the 14th generation of the International Geomagnetic Reference Field (IGRF-14), comprising a Definitive Geomagnetic Reference Field (DGRF) for epoch 2020 and a IGRF model for epoch 2025. Our models utilize high-quality scalar and vector magnetic measurements from the Swarm satellite constellation, supplemented by ground-based observatory data. Data selection procedures were carefully designed to minimize external contamination, emphasizing observations collected during geomagnetically quiet conditions and within Earth's shadow regions. Spherical harmonic expansions truncated at degree 13 were employed, balancing spatial resolution with suppression of small-scale noise. Gauss coefficients were estimated through a two-step inversion process, beginning with linear inversion of vector measurements and followed by nonlinear refinement using scalar intensity data. Our candidate models aim to effectively represent the spatial structure and secular variation of Earth's core-generated magnetic field. The presented methodology and resulting models contribute to ongoing efforts in geomagnetic field modeling, potentially supporting scientific research and practical applications that depend on accurate geomagnetic referencing.

## AS25-1374

# Physics informed neural networks at the service of geodynamo research

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We present an alternate methodology for obtaining source model representations of the geomagnetic core field with the help of physics informed deep learning.
In an effort to extract representations meaningful with respect to a uniquely challenging physical system such as the geodynamo, our approachan took a somewhat different direction than currently prevalent physics informed methods and made use of domain adversarial training.
In addition to an interpretative summary of published results, the main emphasis will be on demonstrating this training technique which enables a network trained mainly on physical model data to handle actual geomagnetic field data more correctly.
Recent developments and new results will also be disclosed along with some contemplation on potential further research directions.

## AS25-1449

# Usthb Candidate Field Model And Its Secular Variation For IGRF-14

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In this work we describe the derivation of the USTHB candidate field model and its Secular Variation for the 14$^{th}$ generation International Geomagnetic Reference Field. We use 2 years of magnetic data from the *Swarm* mission. Our data set comprised quiet night-time data of Swarm spanning 2023.0–2024.9. Data to reduce external perturbations, data selection based on geomagnetic indices was used to minimize the external field contributions. These data were fitted by a spherical harmonic expansion with an internal field of maximum degree/order 13, a secular variation of maximum degree/order 8, a lithospheric field of maximum degree/order 30, an external field of maximum degree/order, A Candidate model of the geomagnetic field IGRF-14 and its secular variation estimates for 2025.0–2030.0 are presented. Improvements gained by the new models are also discussed.

# A05 Current developments of ground based geomagnetic observatories and advances in automated instrumentation, data analytics and higher time-resolution measurements

## AS25-0051

## SQUID magnetometer in geomagnetic observations: numerical calibration and alignment using geomagnetic storm data

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A dual axis high-temperature-superconductor SQUID has been running continuously >4 years at SANSA Space Science (HER), co-located with two fluxgate magnetometers. The SQUID is a variometer with +-500 nT range with high speed data (400 and 2 Hz, respectively) and low noise below 0.2 pT/√Hz at 10 Hz. The orientation is approximately the local H and Z directions. Calibrating the SQUID sensitivity and alignment to a reference frame cannot be done mechanically, as the sensors are immersed in a LN2 bath in a dewar. In order to align the SQUID to the geodetic frame (XYZ), we propose a numerical method based on field variations. We used the Mother's day geomagnetic storm, 10–12$^{th}$ May 2024. Both SQUID and HER XYZ observatory data were high-passed above 0.1 mHz to remove offsets and long-term drift. During the storm the amplitude of the variations in this frequency band was approximately 500 nTpp, during which the SQUID Z axis displayed up to 120 nTpp difference to HERZ, indicating misalignment. We calculated the 3x3 matrix A which describes alignment of raw SQUID data S' to HER XYZ data: A = S'\HER. The A matrix includes the rotation from a rough magnetic frame to geodetic, but also orthogonalization of the SQUID axes and gain corrections. The missing second (h) axis of the SQUID was created from a co-located fluxgate magnetometer. After calculating the aligned SQUID data S=S'A (with the fluxgate h axis), we obtained residuals below 1 nTrms in SQUID X and Z axes, which is a significant improvement.

## AS25-0163

# Strange behaviour of PPM baseline at Budkov (BDV) observatory in years 2022–2023

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Since start of DI-flux measurements at Bukov in 1990's, PPM baseline was determined from 22 (manually processed) values measured with PPM at main pillar at the end of each six non-magnetic theodolite DI-flux procedures. In 2015, measurement with PPM at main pillar was extended to tree hours. PPM baselines was processed manually from this three-hour long record, but baselines for (up-to three) triaxial fluxgates (FGMs) and one set of Bobrov variometers with proprietary photo-converters (TPM) set was still computed from "old fashioned" 22 values of PPM measurement. For closing of year 2021, routines (APM) for automatic processing of PPM was programmed. Routines are based on distributional analysis (one-dimensional cluster analysis) of long (8 hours+) data. Baseline of PPM for whole year is determined at first, then processing of DI-flux measurements using finally-based PPM is done for determination of baselines FGMs and TPM. This method worked well in 2021. In 2022, we started regular measurements with second PPM (mainly for determination of its constant). The strange behaviour starts between 26. 4.–11. 5. 2021 by step of +400 pT on APM results. It ends by step of the same value in opposite direction between 7. 2.–17. 2. 2023 (exact time can not be determined due-to interval between absolute measurements), Between this time, APM results shows abnormal variance (approx. five-fold higher—near constant in time). After 17. 2. 2023 APM results shows normal behaviour—the same as before 26. 4. 2021.

## AS25-0329

# Ground-based Geomagnetic Observations on the Volcanic Island of Jeju: A New Approach Overcoming Underground Magnetic Field Influences

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During the solar maximum, increased solar activity has led to more frequent geomagnetic storm warnings, intensifying the impact of space weather. The coronal mass ejection (CME) event in 2021 caused GPS signal errors and power system overloads in some regions. These cases highlight the widespread effects of space weather disasters and underscore the need for a reliable geomagnetic storm warning system. In response, Korea Space Weather Center (KSWC) produce and disseminate forecast and alert to mitigate space weather impacts and ensure national and societal safety. To enhance space weather monitoring, KSWC established a new geomagnetic observatory in Jeju in December 2023. Since Jeju is a volcanic island, the underground environment is influenced by magnetic fields. Therefore, unlike traditional underground observatories, the observatory was installed 1 meter above the ground and consists of an absolute measurement room, a scalar observation room, and a vector observation room. Data collected in 2024 met INTERMAGNET membership standards, maintaining an annual baseline variation within ± 5 nT and successfully capturing geomagnetic changes during G4-level storms. This study analyzes geomagnetic variations recorded at the Jeju above-ground observatory and its response to intense geomagnetic storms. Additionally, the observatory's operations and preparations for INTERMAGNET are also discussed.

## AS25-0356

# From soil moisture to subsurface currents: Advancing geomagnetic data correction with AI

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Environmental influences, such as temperature, are well-known in geomagnetic observatory practice. Many geomagnetic observatories record not only geomagnetic variations but also fluctuations in environmental properties to correct geomagnetic data. At Tihany Observatory, several environmental parameters have been continuously monitored. This dataset provides an excellent opportunity for data processing, as the area's sediment deposits exhibit unstable magnetic susceptibility that is modulated by soil moisture. In our initial study, we explored baseline fluctuations using a deep learning (DL) method, specifically a linear regression model. As a result, we developed a real-time data correction model.

The presentation will address several key questions:

- What would be the outcome of using a more advanced DL model for prediction?
- Can incorporating additional environmental parameters (e.g., resistivity of the soil, precipitation, humidity, soil temperature) improve the data correction model?
- What is the geophysical interpretation of the heatmaps produced by the DL model?

The objectives of our research are twofold:

1. To gain a deeper understanding of the environmental effects on the observatory and the magnetometers.
2. To develop a real-time data correction method that can be used for anomaly detection, particularly in the presence of anomalous subsurface currents.

## AS25-0504

# Analysis of the local geomagnetic Index: First results from the equatorial geomagnetic station at Entoto Observatory

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The newly deployed Entoto Magnetometer Station, located near Addis Ababa, Ethiopia, represents a significant advancement in geomagnetic monitoring in the African sector. Established through a collaboration between the South African National Space Agency (SANSA), Ethiopia's Space Science and Geospatial Institute (SSGI), and the German Centre for Geosciences (GFZ), the station is equipped with a LEMI-025 fluxgate magnetometer and a GSM-90 Overhauser sensor. These instruments provide high-resolution data for studying geomagnetic field variations, space weather disturbances, and the equatorial electrojet.

Preliminary results indicate distinct geomagnetic signatures influenced by local ionospheric currents and external solar activity. The station's ability to generate a local K-index enhances regional space weather monitoring, offering critical insights into geomagnetic storms and ionospheric variability. By addressing observational gaps in Africa, the Entoto station contributes to global geomagnetic research and space weather forecasting. This talk presents an overview of the station's setup, data processing methodology, and initial findings, highlighting its role in advancing geomagnetic science in the region.

## AS25-0554

# Upgrading the Data Acquisition Capability of the Panagyrishte (PAG) Geomagnetic Observatory with one-second measurement system

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High-resolution geomagnetic data is essential for studying rapid geomagnetic variations, space weather phenomena, and geophysical processes. One-second geomagnetic observatory data provides significant advantages over one-minute data, particularly for applications requiring high temporal resolution. In this regard, an upgrade was performed to implement one-second data acquisition thus enhancing the monitoring capabilities of the Panagyurishte geomagnetic observatory.

Established in 1937, the Panagyurishte Geomagnetic Observatory (PAG) is situated in central Bulgaria. PAG holds the longest continuous geomagnetic data series in the Balkans and has been a member of INTERMAGNET since 2007. Operated by the National Institute of Geophysics, Geodesy, and Geography (NIGGG-BAS), it provides continuous, high-quality geomagnetic field measurements essential for space weather monitoring, geomagnetic research, and navigation. The transition to 1-second data acquisition enhances PAG's ability to detect and analyse short-term geomagnetic fluctuations, such as geomagnetic pulsations, sudden storm commencements, and other transient phenomena.

The upgrade involved installing a new system comprising a LEMI-025 Fluxgate magnetometer (Lviv Centre of ISR, Ukraine), which meets the 1-second INTERMAGNET data standard, and a GSM-90 Overhauser magnetometer (GemSystems, Canada) for total field measurements. The MARTAS data acquisition software was integrated into the system to ensure smooth data processing.

With this upgrade, PAG strengthens its role as a valuable geomagnetic observatory in the global monitoring network. It became the first observatory on the Balkan peninsula to provide high-resolution one-second data supporting research on geomagnetic field variations, short-period disturbances, and geomagnetic modelling.

## AS25-0576

# World Data Centre for Geomagnetism, Edinburgh: New data portal, application programming interface (API), and metadata tools

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The World Data Centre (WDC) for Geomagnetism, Edinburgh serves the geomagnetism community providing access to geomagnetic data records for over 550 magnetic observatories worldwide, both past and present. It holds observatory minute, hourly, and annual means, as well as yearbooks, magnetic survey data and activity indices, with data reaching back to the early 1800s. It has recently been certified as a trustworthy data repository by the CoreTrustSeal Standards and Certification Board.

In October 2024, new WDC data portal was released providing a step-change in accessibility to these important geomagnetic datasets. We will describe how this new data portal (https://wdc.bgs.ac.uk) enables users to interactively search for, and access geomagnetic datasets. New functionality that allow users to easily view data availability, plot data, view observatory metadata, and download datasets in a range of data formats will be demonstrated. This data portal is powered by a new API (Application Programming Interface) which has been developed to deliver the observatory data and metadata programmatically. We will outline the various endpoints that are available to users to incorporate into their software. In addition, we will introduce new tool which has been developed to allow geomagnetic observatory operators to review, update, and enhance the metadata records currently held for observatories.

## AS25-0604

# Upgrade of the geomagnetic observatory Neumayer Station III, Antarctica

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Neumayer Station III (IAGA code VNA, latitude -70.683°, longitude -8.283°) is a geomagnetic observatory in Antarctica and became an INTERMAGNET observatory in 2014. It is scientifically very interesting for core field, ionospheric and magnetospheric studies as it located at the southern flank of the South Atlantic Anomaly as well as just north of the auroral oval and at an L-shell of 4.2. The location is on a moving ice shelf at a coastal region with significant snow accumulation and this brings more peculiarities. Firstly, the observatory is drifting with about 160 m per year and the crustal magnetic field changes along the drift path have to be corrected for. Secondly, the ice shelf is rotating with about 0.25° per year and any geographic azimuth is constantly changing. Thirdly, due to the large snow accumulation of 1 meter per year, the observatory is increasingly buried by snow. As a consequence, the observatory is designed as a tunnel in the snow and geographic north is determined by a north-seeking gyro. We will report about a new, nonmagnetic tunnel about 60 m in length and how it was built and equipped with instruments and how they are calibrated. Additional geospace instruments at Neumayer are an induction coil, a GNSS receiver, an aurora camera and a riometer.

## AS25-0696

# Advancements in magnetic observatories in northern and southern Greenland

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Qaanaaq Observatory (THL), one of the northernmost geomagnetic observatories, is located at 84° Quasi-Dipole geomagnetic latitude in northwest Greenland. Due to the sparse distribution of observatories, Qaanaaq plays a crucial role in monitoring Earth's magnetic field in the polar cap. Since 1956, it has provided high-quality data and remains one of the only two observatories contributing to the IAGA-endorsed PC index. However, ongoing construction and increasing human activity in the vicinity will likely introduce magnetic disturbances in the coming years. To ensure the continued collection of high-quality data from northern Greenland, a new observatory has recently been established at Pituffik Space Base (PIF), located approximately 100 km south of Qaanaaq at 83° Quasi-Dipole geomagnetic latitude. In addition, significant upgrades to the Narsarsuaq Observatory (NAQ) were completed in 2024, securing the continuation of its over 50-year-long time series of high-quality geomagnetic data. This poster details the development process for both observatories, including the construction of magnetically clean observatory buildings, instrument installation, and the initial analysis of promising baseline stability and calibrated data.

## AS25-0757

# Establishment of the Zero Magnetic Field Laboratory (ZBL) at the Széchenyi István Geophysical Observatory (SzIGO)

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The Zero Magnetic Field Laboratory (ZBL) is being developed through a collaboration between the HUN-REN EPSS and the HUN-REN Wigner RCP, with support from the European Union (GINOP-2.3.3–15–2016–00016). The unique laboratory environment is being established at the SzIGO, Nagycenk, Hungary, (INTERMAGNET code: NCK) where the surface geomagnetic field is reduced by five orders of magnitude in room sized volume. This will enable specific space technology developments, space science experiments, material science research, and biophysical investigations.

The reduction of the geomagnetic field is achieved in two stages: active compensation and passive shielding:

- **Active Compensation System (ACS)**: The core of the ACS is a coil system of Merritt geometry. Its specifications are based on preliminary analytical and numerical simulations, which aimed to create a homogeneous magnetic field over a large volume in the system's focal area.
- **Passive Shielding**: Further reduction of the residual field is achieved by a shielding chamber constructed of a high magnetic permeability material, called μ-metal.

The combined effect of these two stages reduces the surface geomagnetic field to the **sub-nanotesla range** within a **1.5 m × 1.5 m × 1.5 m** volume.

The compensation magnetic field is updated at 1 Hz rate. The required adjustments are based on real-time observation of the geomagnetic field of the Observatory. The ACS is driven by a set of 16 programmable power supplies which are protected against quick variations of the geomagnetic/compensation field of geomagnetically disturbed periods by low level stabilized slew rate of driving currents and hardware protection in the current path.

## AS25-0763

# Digitalisation and analysis of hourly mean values recorded at Sao Miguel (SMG, Azores) geomagnetic observatory from 1965 to 1977

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The Sao Miguel Observatory (SMG), operated by the Azores Meteorological Service and located 4 km northeast of Ponta Delgada in the Azores archipelago, Portugal, measured the geomagnetic field continuously from 1911 to 1977. However, only two months of hourly mean values (for 1965) and yearly mean values are available at the WDC repository. In this project, we digitized 13 years of hourly means of H, D, and Z spanning from 1965 to 1977. The entire time series was analyzed and adjusted for obvious jumps and outliers, which mostly happen in the last three years of the data set. The resulting data was cross-checked against the existing records at the WDC. The hourly data will be made available for the scientific community. This data is relevant because it is the only hourly means data from the North Atlantic region during this period, with the geomagnetic observatory in Coimbra being at a distance of 1500 km and Tenerife at 1340 km.

## AS25-0845

# More accurate assessment of local magnetic field variations due to extreme geomagnetic storm

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Geomagnetic indices are routinely used at observatories located on the Earth's surface. At mid-geomagnetic latitudes, this is the standard K index and the daily geomagnetic activity A is calculated from it. The K index mainly indicates changes in the horizontal component of the magnetic field due to the influences from space. However, this index cannot be used to estimate influences from the Earth's interior and does not fully reflect the actual effect of individual geomagnetic storm.

The geomagnetic observatory PIA (Piran, Slovenia) is located on the Adriatic tectonic microplate, which is an excellent natural geophysical laboratory. The magnetic noise level measured on it is higher than on the neighboring Eurasian tectonic plate. One of the sources of this noise is also the tension of this microplate, which has the greatest effect in the vertical direction. At the observatory on May 11 and 12, 2024, the magnetic storm of the Extreme category was measured, which is among the 20 most powerful storms in the last 500 years in terms of the created aurora. For this storm, geomagnetic indices and the daily acceleration of the change in magnetic field energy density were calculated. This combined estimate of the change in the local magnetic field was tested during one effective rotation of the Sun and found to be better than using the geomagnetic index alone. Therefore, this combined approach will be used to evaluate both past and future events measured at the observatory.

## AS25-0854

# Characterisation and mitigation strategies of artificial magnetic noise at Chambon la forêt observatory

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The magnetic observatory of Chambon-la-forêt (CLF) is located in the large forest of Orleans in central France. The observatory started its operations in 1936 and operates continuously since then. Data acquisition systems providing 1 Hz sampling of magnetic variations have been deployed in 2009. Three additional measuring huts have been constructed in 2015 scattered on the land of the observatory, to always guarantee the availability of unperturbed data in case of renovation works need to be conducted on the site. It appears however that an external source of noise is present, providing a small perturbation of ~ 1 nT over a period of several minutes. Short measuring campaigns have been conducted in various locations around the observatory, indicating that the source of this noise is the railways Paris-Orleans, operated using 1500 V DC current. Is is located at 27 km distance from the observatory. More recently we faced a local source of noise, impacting only some of the scalar magnetometer and the current mitigation is realised by moving this instrument out of the location affected.

## AS25-0895

# Tuning of low magnetic field in the focal volume of the ZBL

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The Zero Magnetic Field Laboratory (ZBL) is established at the Széchenyi István Geophysical Observatory, Nagycenk, Hungary in frame of a collaboration between the HUN-REN EPSS and the HUN-REN Wigner RCP, with support from the European Union (GINOP-2.3.3–15–2016–00016). The unique laboratory environment aims to realize subnanotesla magnitudes of magnetic induction field in the focal volume as a unique environment for a wide range of scientific experiments and studies. The reduction of the geomagnetic field is achieved by means of a dual mechanisms:

1. active compensation is realized by two independent triaxial Merritt coil system:
   - the robust one is for the main field and the large amplitude component of the geomagnetic variation.
   - and the one-turn Merritt coil system is for the fine tuning.
2. The residual field is further reduced by passive shielding off a by a 2-layer mu-metal chamber of 3 m x 3 m x 3 m external dimensions.

The control of the compensating coil currents is going to be based on a) a local, but far enough observation and b) the reconstruction of the central field by three independent approaches of modeling the magnetic field inside the chamber:

- analytical method means a polynomial approximation,
- numerical modeling,
- and by machine learning tool developed in Python

to reconstruct the 3 component of the focal magnetic field by means of data from 6 vector magnetometer installed around the focal region. The presentation provides a short introduction of the development of these control mechanisms under development.

## AS25-0965

# Peer-review of data products: an automated assistance system for INTERMAGNET

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A peer review system is widely considered essential to ensure the quality and accuracy of scientific research by allowing experts in the field to evaluate and provide feedback on the work before it is published. Such reviews help toidentify and correct errors, inconsistencies, or gaps in methodology, analysis, or interpretation, thus improving the overall reliability of the research. Although a peer-review system is widely used for scientific publications, pure data products are typically not reviewed bythe science community. An exception are data products submitted to INTERMAGNET. Due to the large amount of data, particularly due to new 1 Hz data products, a traditional, purely manual review process is not applicable. The INTERMAGNET ROBOT (short IMBOT) has been developed to provide automatic routines to convert and evaluate INTERMAGNET (IM) data submissions. IMBOT continuously access the upload directory of the geomagnetic information nodes and checks for new or modified data submissions. It analyzes data sets regarding most typical issues, can handle format conversions and checks for inconsistencies. The primary aims of IMBOT is to (1) simplify one-second and one-minute data submissions for data providers, (2) to speed up the evaluation process significantly, (3) to consider current IM archive formats and meta information (e.g. on leap seconds), (4) to simplify and speed up the peer-review process and finally (5) to reduce the workload of human data checkers. This automated system makes data review faster and more reliable, providing high-quality data for the geomagnetic community.

## AS25-0978

# Deploying magnetic variometer stations in France: progress and data assessment

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The magnetic observatory service at the Institut de Physique du Globe de Paris (IPGP) provides high-precision ground-based geomagnetic measurements and data products. It operates the French National Magnetic Observatory in Chambon-la-Forêt (CLF), along with a broad network comprising ten overseas observatories and eleven repeat stations.

Since 2022, the service has been establishing variometer stations in remote areas with low anthropological noise across metropolitan France to ensure accurate and reliable geomagnetic observations while gradually replacing nearby repeat stations. These serve as reference bases for magnetic surveys, support ionospheric and magnetospheric studies, and provide local magnetic activity indices. The current network includes four stations: MZH in western France, and three forming a north-south alignment with CLF: HLF in the north, CMF in central France, and LZC in the south. Each station delivers near real-time vector and scalar measurements of the local magnetic field. Additional installations are planned to expand coverage across the territory.

Annual on-site visits are conducted for maintenance and absolute measurements to ensure precise instrument orientation and monitoring of long-term variometer drift. All data acquisition follows INTERMAGNET standards, maintaining compliance with international guidelines for data format and equipment reliability.

This presentation provides an update on the recent developments in the variometer station network in France, following our previous report at the 20th IAGA workshop in Vassouras. It highlights the latest installation progress, site-specific adjustments, and an initial assessment of data quality.

## AS25-0995

# Analysis of geomagnetic field variation in the Korean Peninsula from 2014 to 2023 using Cheongyang Geomagnetic Observatory data

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The Cheongyang Geomagnetic Observatory has been operated to study the long-term geomagnetic variations in the Korean Peninsula and has shared geomagnetic observation data and definitive data with INTERMAGNET since 2014. The observatory is located in a mid-latitude region (Lat 36.370° N, Lon 126.854° E) and was established at a site more than 5 km away from major roads to minimize the influence of artificial magnetic disturbances. This study analyzes 10 years of observation data (2014–2023) to investigate the geomagnetic secular variation in the Korean Peninsula. The following analyses were conducted to achieve this objective. First, the definitive data produced at the Cheongyang Observatory were compared with the geomagnetic observatory data from neighboring countries to assess long-term geomagnetic variations. The definitive data processing was performed using GDASView, a Java-based software developed by British Geological Survey(BGS). Additionally, periods of geomagnetic quietness were selected to analyze long-term geomagnetic variations. To ensure reliable data selection, lightning damage records were examined to assess their impact on geomagnetic measurements. Finally, to verify the reliability of the analysis results, a comparative analysis was conducted using International Geomagnetic Reference Field(IGRF), a global geomagnetic model. The analysis results indicate that the geomagnetic field in the Korean Peninsula exhibits a trend similar to that of neighboring geomagnetic observatories, with the Y-component continuously decreasing, while the Z-component and total geomagnetic field show a continuous increase.

## AS25-1000

# Current Status and Quality Improvement at the Cheongyang Geomagnetic Observatory

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South Korea is surrounded by the sea on three sides, and due to rapid urbanization, areas that were once suitable for stable geomagnetic observations are now increasingly affected by external factors causing geomagnetic distortions. However, the Cheongyang Geomagnetic Observatory experiences minimal marine influence and maintains a stable distance from urban areas and external environmental factors, making it an ideal location for geomagnetic observations. The observatory was established in 2009, and in 2013, it was recognized for the quality and precision of its geomagnetic data, leading to its inclusion in INTERMAGNET. The observatory produces annual definitive geomagnetic data using a proton magnetometer for total geomagnetic field measurements, a three-axis fluxgate magnetometer for measuring variations in geomagnetic field components, and a manual absolute magnetometer (D/I meter) for measuring declination and inclination. Additionally, in 2022, an automatic absolute measurement instrument was introduced to enhance efficient quality management and is currently under trial operation. To improve data quality, the observatory removes outliers from daily raw data and conducts weekly on-site inspections to manage external environmental conditions. In this study, absolute measurement data with a K-index of 4 or higher were classified using automatically observed absolute declination and inclination at hourly intervals, and a stable baseline was derived. Furthermore, the impact of Site Difference variations between the absolute measurement room and the proton measurement room on the degradation of definitive data quality was evaluated.

## AS25-1020

# A permanent magnetotelluric reference station in Wittstock, Germany

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The sources for the magnetotelluric (MT) method are naturally occurring electromagnetic field variations. Electromagnetic currents over a wide range of frequencies are excited in the Earth's ionosphere by solar activity and global lightning discharges. Although these sources are available anywhere on Earth at any time, their signal strength varies considerably. The remote reference technique is an effective way to improve the quality of MT data by referencing electromagnetic fields recorded at a local site to simultaneously recorded undisturbed fields at a remote site. The remote reference approach is routinely used in areas with high levels of man-made electromagnetic noise. In addition to magnetic field data, broadband electric field data are continuously recorded at the reference site, which is important for quality control or ground testing of GIC models, for example. All data are recorded as time series with two SPAM.Mk.IV systems since 2012. For ease of use, the data are reorganised as three virtual MT sites covering a wide frequency range. Site 991 consists of a Geomagnet 3-component fluxgate magnetometer with a typical sampling rate of 1 Hz. Site 996 samples at 250 Hz with Metronix MFS06 induction coil magnetometers, while site 997 records high frequency data with Metronix MFS07 sensors with varying sampling rates between 2.5 kHz and 25 kHz. Electric field recordings with non-polarisable Ag/AgCl electrodes are available for all sites. We show time series examples, discuss data quality control in terms of MT transfer functions and explain how to access the data.

## AS25-1045

# Analysis of scalar and variometric data of the "Faraday Islands (Argentine Island)" observatory during geomagnetic disturbances

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The Geomagnetic Observatory "Faraday Islands (Argentine Island)" at the Ukrainian Antarctic "Akademik Vernadsky" station has nearly seventy years of history of observations in Antarctica. After a recent modernization, in the 2019 and 2024 seasons, geomagnetic signals are recorded using two LEMI-025 variometers compatible with the 1-second INTERMAGNET standard and an Overhauser GSM-90 magnetometer. In our previous study we found that the GSM-90 counts were approximately 0.4 seconds ahead of the LEMI-025 counts. This was done by processing the 1-second data of GSM-90 and LEMI-025 acquired during the strong magnetic storm on May, 10–11 2024. After applying the time shift correction to the GSM-90 records and baselines correction to the LEMI-025 records, the maximal total field difference became within 1.5 nT peak-to-peak, i.e., it decreased by a factor of 5 compared to the uncorrected signal. However, even after correction, the difference signal is partially correlated with the total field variations.

In this work we attempt to estimate such bias values that reduce the LEMI-025 recordings to the GSM-90 sensor location, taking into account the magnetic vectors difference at the absolute and scalar pillars. For this purpose we use a linearized model linking the scalar and components measurements and an iterative least squares estimation of the four parameters: three bias values and a free parameter. The latter parameter takes into account the possible scale factor and orthogonality errors of the variometer. As a result, an additional 2-fold reduction of the total field difference signal was achieved.

## AS25-1056

# Autonomous Instrument Network for Coordinated Observations at Remote Antarctic Locations

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We present the development and operation of an automated ground-based instrument network to be deployed at remote locations across Antarctica. The network is designed to house cutting-edge Earth and space science instruments, collecting data autonomously in this harsh environment with minimal service visits required. The power and telemetry platforms integrate solar panels, wind turbines, batteries, and two-way satellite communication for data acquisition and house-keeping. Originally developed in the 1980s as part of the United States National Science Foundation (NSF)-funded Automatic Geophysical Observatory (AGO) program, the network has successfully operated across the Antarctic ice shelf. A newly designed AGO system has been developed to enhance support in several areas: (a) power generation in the 100 to 200 W range, (b) power conditioning and control, (c) robust engineering for polar climates, (d) data acquisition, units, and transmission services, and (e) general polar field support. This new AGO system will be deployed in the deep polar cap regions of Antarctica as part of the Antarctic Korean Route Expedition project, led by the Korea Polar Research Institute (KOPRI). In this presentation, we review the new system, deployment plan, and potential scientific investigations facilitated by the new network.

## AS25-1069

# Evaluation of data and baselines from the new Port Stanley Observatory site

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Port Stanley magnetic observatory (PST) was established in 1994 on Sapper Hill, near Stanley, Falkland Islands, and has been an INTERMAGNET observatory since 2003. PST results are of particular significance in relation to the global modelling efforts as it is located in a favourable position to monitor the evolution of the South Atlantic Anomaly (SAA).

Third-party communications infrastructure, also situated on Sapper Hill, has progressively increased since the observatory was installed. This has resulted in increasing RF interference affecting the observatory instrumentation and a subsequent degradation in the quality of observatory data especially over the last 10 years. Several mitigations have been made however, with the communication infrastructure expanding, data quality continues to erode, and the time taken to employ the mitigations and corrections is unsustainable. Taking into account these concerns, a decision was made to relocate the observatory, approximately 3.5 km east of the original site. Over the last five years, work has been ongoing to establish a new site, PST2, that would eventually supersede the current observatory under the PST IAGA code. PST2 became operational in December 2023 with first data available from 2024.

We briefly describe the installation of the new observatory site and the data processing pipeline. Results from PST2 are presented and compared to the original PST location to enable the evaluation of the long-term stability of the dataset. We also appraise the baselines at the new site and present a case to switch the primary observatory site to the new location from 2025.

## AS25-1099

# From analogue magnetograms to the digital era: data processing and technological update at Fúquene Geomagnetic Observatory in Colombia

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The Fúquene Geomagnetic Observatory (FUQ) is located in Colombia (5.4376° N, 73.7343° W, WGS84), making it a strategic site for studying geomagnetic behavior and space weather phenomena near the equator. FUQ is operated by the Colombian Geographical Institute Agustín Codazzi (IGAC). Geomagnetic data from the observatory was submitted to the World Data Center (WDC) between 1955 and 2013.

In 2024, a significant effort was undertaken to digitize analogue magnetograms and absolute measurements, apply corrected baselines, and conduct data quality control. By the end of the year, we successfully sent 2014–2015 data to the WDC and are processing 2016–2022 data. We are particularly interested in presenting the progress made in processing 2014–2022 analogue magnetograms.

We describe FUQ's transition from analogue magnetograms (1-hour intervals) to digital magnetograms with higher resolution (1-second to 1-minute intervals). Between 2022 and 2023, observatory operations were suspended due to obsolete instruments and damage from two lightning strikes. However, FUQ has since undergone significant modernization. In October 2022, the British Geological Survey (BGS) donated a triaxial fluxgate variometer (FGE). Additionally, between 2022 and 2024, IGAC acquired: Two Diflux theodolites, a MAGREC data collector, an ObsDaq converter, three proton precession magnetometers (GSM-19), a LEMI variometer. With this new instrumentation, FUQ resumed operations in 2024, and we are preparing to install the second variometer (LEMI) to ensure continuous data collection.

Finally, we will present advancements in processing the new digital data from 2024–2025 using the MagPy software, with the goal of incorporating this and future datasets into INTERMAGNET.

## AS25-1159

# Quality of Geomagnetic data, its impact on data products, and interpretation

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In this present study, 12 years of data from the HYB observatory and 8 years from CPL Observatories have been utilized to examine the characteristics of data at different conditions to identify and evaluate sources of error during the measurement of magnetic fields at low-latitude stations in the Indian region. At Hyderabad(HYB) due to AC power lines continuous random noise in Z and F components produces a 3.5% error in 1-sec data and +/- 0.5 nT error in 1-min data whereas after removing noise in data, accuracy is improved to +/-0.2 nT. At Choutuppal(CPL), 50 km due east, we noticed periodical negative noise signatures in the 2 Hz H, D, and Z components. 25% of H data samples were affected by error and decreased real value by about -0.5 nT less. Similarly, 6% of D data samples were affected by the error and -0.02 min decreased, and 6% of Z data samples were affected by the error and -0.4 nT decrease from the real value. Due to these errors in absolute data accuracy were observed in 3 nT in H, 1 min in D, and 5 nT in Z during one year. Upon application of advanced processing techniques, absolute data quality reached up to 1.8 nT in H, 0.5 min in D, and 3 nT in Z over 1 year. The final absolute data accuracy improved to ±2.5 nT for 1 year. Investigations at local and regional scales have been conducted and the results are presented.

**Keywords**

Geomagnetic Observatories, AC power lines, instrumental errors, absolute observations, local and regional characteristics.

## AS25-1165

# Baseline Calculation and Temperature Correction Method for Definitive Data Production Based on AutoDIF at Cheongyang Geomagnetic Observatory, South Korea

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The Cheongyang Geomagnetic Observatory introduced an automatic absolute measurement instrument (AutoDIF MKII) in 2022 to improve the efficiency of observatory operations and data quality. Currently, this instrument is being used to measure declination and inclination. However, discrepancies exist between automatic and manual absolute measurement data, which have been identified as key factors hindering the stable derivation of the baseline. Therefore, since March 2022, automatic and manual absolute measurement data have been compared and analyzed to perform corrections on automatic absolute measurements and propose a baseline calculation method for definitive data production. Although automatic and manual absolute measurements exhibit similar trends, differences of 0.05° in declination and 0.02° in inclination were observed. Compared to the stable collimation angles of 0.005° in manual absolute measurements, automatic absolute measurements exhibited a collimation angles ranging from 1.1° to 1.3°. To address this issue, the declination was adjusted for the offset caused by the collimation angles and magnetometer offsets, and the inclination was corrected using the correlation with the Z-baseline, minimizing differences with manual absolute measurement data and stabilizing data quality. Furthermore, analysis of temperature variations in the fluxgate magnetometer measurement room revealed that daily fluctuations in the G-value were caused by temperature changes, with a fluctuation range exceeding 1 nT. Consequently, annual and daily temperature corrections were performed to improve the quality of the baseline and definitive data, minimizing daily fluctuations in the G-value and reducing its annual fluctuation to within 1 nT.

## AS25-1210

# The magnetic observatory of Coimbra (COI): status, challenges, and future directions

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The Magnetic Observatory of Coimbra (COI), founded in 1864 and currently operated by the Geophysical and Astronomical Observatory of the University of Coimbra (OGAUC), is one of the most ancient observatories in operation in the world. Over its long history, COI has sought to adapt to advances in instrumentation and observational practices. The most recent major upgrade occurred in 2007, when classic torsional magnetometers with suspended or balanced magnets were replaced by a modern digital fluxgate variometer and standard set of absolute instruments – a DI-flux and an Overhauser scalar magnetometer. This upgrade improved baseline stability and significantly enhanced COI's data quality. However, ongoing urban expansion has continued to affect the observatory's performance, particularly high-frequency signals, compromising certain space weather studies.

To ensure the continuation of high-quality geomagnetic observations in central Portugal, OGAUC and IPMA (Portuguese Institute for Sea and Atmosphere) plan to establish a new observatory at the Viseu Meteorological Centre (VIS), 70 km northeast of Coimbra. To assess site feasibility, a variometer was deployed to record the variations of the geomagnetic field's XYZ components at 1 Hz over the course of a year. Data analysis comparing VIS with COI and SPT (Spain) observatories revealed no anthropogenic noise at VIS (and SPT), suggesting favorable conditions for undisturbed signal acquisition across the analyzed frequency range.

In addition to providing a brief overview of COI's long history and current operating status, this communication aims to present and discuss the ongoing studies related to a possible relocation to the new site in Viseu.

## AS25-1213

# A stochastic estimation of observation baseline values directly using angle data in the geomagnetic absolute measurement

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Ground-based magnetic observatories are operated worldwide to monitor the geomagnetic field and its variations. Generally, their observations consist of geomagnetic variational measurement made by using a fluxgate magnetometer, and geomagnetic absolute measurement performed regularly to calibrate the variational data. In the latter a declination-inclination (DI) magnetometer is used to observe the geomagnetic DI by manual angular measurement. In principle one can absolutely define the geomagnetic field vector components by combining DI data with total intensity data provided by a separate scalar magnetometer. The calibration value for the variational measurement data, named observation baseline value, is derived by taking differences between the absolute measurement data and the fluxgate magnetometer data for each time of the absolute measurement.

We developed a method to estimate observed baseline values directly from angular data obtained with a DI-magnetometer. Besides the three observed baseline values for the declination and the horizontal and vertical forces, parameters inherent to the DI-magnetometer are jointly estimated: horizontal and vertical collimation errors of the theodolite, and offset of a single-axis fluxgate magnetometer. Observation baseline values and their variances are estimated with stochastic inversion approach minimizing the L1-norm. We discuss two merits of the method: 1) Observation baseline values, as well as raw angular measurement data themselves, can be evaluated by referring to their model fittings. 2) Without requiring any scalar magnetometers, observed baseline values can be derived, making it possible to use absolute measurement records to calibrate variational data in the past at such stations as Syowa Station, Antarctica.

## AS25-1308

# Filling the gaps: New variometers in the UK for space weather monitoring

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Three long term INTERMAGNET-standard observatories (Hartland [HAD], Eskdalemuir [ESK] and Lerwick [LER]) have operated in Britain for decades covering latitudes from 50° to 61° N degrees. However, due to their location, there is limited longitudinal coverage (-1° to -4° E) which does not provide sufficient coverage across the available 10° longitude extent of the British Isles. In 2022, three new variometer sites were installed in western Northern Ireland (Florence Court, FLO), central England (Market Harborough, LEI) and south-eastern England (Herstmonceux, HTX) to complement the existing observatory network. These provide high quality magnetic variation data, though not absolute level, for space weather monitoring. We describe the instrumentation, site environment, and data collection protocols. With the new monitoring sites we can apply the data in space weather research, for example to improve the measurement of the auroral oval extent and intensity during the May 2024 extreme magnetic storm.

## AS25-1330

# A new automated instrument for geomagnetic absolute measurements

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The geomagnetic absolute measurement is the key calibration procedure of ground-based observatories producing baseline corrected variometer data.

In most geomagnetic observatories the absolute measurements are carried out manually using a declination inclination magnetometer (DIM), typically once a week. At these instruments a single axis magnetometer is mounted on the telescope of a non-magnetic theodolite. It is often a problem, especially in remote observatories, that the measurement needs the regular presence of a trained operator.

In the past decades automated absolute geomagnetic instruments have been developed, using slightly different instrument frames and azimuth direction calibration methods than the DIM instruments use, but their usage is still very limited. As a new option, a new type of automated instrument, named as Automatic Digital Station (ADS), has been developed recently. It is a robotized version of the conventional DIM instrument. ADS is based on the well proven non-magnetic Zeiss theodolite. It has two non-magnetic piezo motors, two digital angle readers and a digital camera to replace the manual controls. An external electronics box with embedded software performs the measurement autonomously. The measurement can be executed in a very similar manner than in the case of the manual measurements. In addition to that, ADS offers many new measuring sequences and additional measurement options/goals. ADS has remote access possibility.

In this paper we present some test results of ADS. We demonstrate the benefit of having frequent absolute measurements for several days. We also show some test results of reference mark readings at different conditions.

## AS25-1372

# Small Cosmic Ray detectors as new devices for the permanent study of the Earth's magnetic field with ground-based stations

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Cosmic rays are protons and other atomic nuclei that impact the Earth from deep space. Upon reaching the atmosphere, they collide with other atomic nuclei, producing so-called secondary cosmic rays. All of these are significantly affected by the Earth's magnetic field, producing effects such as the well-known East-West asymmetry, which can be measured by ground-based detectors.

Recently, we introduced a new generation of small, portable particle detectors with high angular resolution, the miniTrasgos, for the regular study of cosmic rays reaching Earth. Four of these detectors have already been installed in Madrid (Spain), Warsaw (Poland), and Puebla and Monterrey (Mexico). Given their high angular resolution (a few degrees) despite their small size, these detectors should be sensitive to variations in the Earth's magnetic field induced by variations in solar activity. In this contribution, we will present the first measurements of this effect with real data.

(Contribution on behalf of the miniTrasgo International Network)

## AS25-1428

# GM4 fluxgate magnetometer: an instrument performance and data quality in comparison with DTU FGE magnetometer at the St. Petersburg Observatory (SPG)

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We present the experience of long-term operation of the three-component flux gate magnetometer GM4 at the St. Petersburg Observatory (SPG). The recordings obtained on GM4 were used for preparation of the definitive data dataset of the one-minute INTERMAGNET standard. The noise characteristics and long-term stability of the sensor baseline are compared with the main variometer of the observatory, which is the DTU FGE. The compliance of the GM4 data with the requirements of the one-second INTERMAGNET standard is discussed. In addition, the process of installation and adjustment of GM4 and the capabilities of the data acquisition system supplied with the sensor are reviewed.

## A06 The future of WDMAM and crustal magnetic anomaly mapping

### AS25-0079

# Compilation of near-earth magnetic data and a new global oceanic magnetic anomaly grid (OMAG)

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Ship-borne magnetic data including those from three-component observation and low-altitude airborne data including digitized Project MAGNET data were compiled to create a global track line data set of magnetic anomalies. Ship-borne data at high sampling rates were reduced by resampling to 1 minute interval and robust low-pass filter was applied to remove high-frequency noise and false spikes. The Project MAGNET data in high-amplitude anomaly areas were also removed. The total numbers of the ship and airborne magnetic anomaly data were about 40,600,000 and 3,100,000, respectively. The standard deviation of all the crossovers was 81.2 nT.

All the track line data were divided into straight-line segments shorter than 120 km. Line leveling was carried out by adding low-frequency corrections to all the track line data to minimize the anomaly differences of all the segment pairs with the pair distances smaller than 15 km (including cross-overs), and the standard deviation was reduced to 31.7 nT after 250 iterations of the leveling calculation.

A new 2-arc min global grid of magnetic anomalies in oceanic areas (OMAG) was created using the leveled data. Nearest existing data of the same isochrons were used to fill areas lack of the data, and the grid values were calculated using the minimum curvature interpolation. Besides lineations due to seafloor spreading, OMAG includes shorter-wavelength components.

## AS25-0208

# Forward modelling of gravity and magnetic data in the presence of topography using a numerical integration scheme with deformable elements

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Potential field geophysical data are frequently used to image geological features in volcanic systems/areas (faults, lithological contacts, alteration zones, geothermal or magmatic reservoirs). However, although crucial, it can prove challenging to accurately simulate data in such regions due to the major influence of strong topographic variations. Here, we develop a new numerical tool for the modeling and inversion of these data that accurately accounts for topography with a reasonable computational cost. The method consists in a numerical integration scheme of the integral equations predicting gravity and magnetic data on deformable hexahedral elements. Topography is accurately reproduced by combining an optimization of the nodes' elevation defining the model's topography and an automatic local refinement in the vicinity of the measurement points. This refinement is based on a convergence criterion of the numerical integration that ensures both an accurate representation of the topography and the reduction of the effect of solution singularities close to observation points. The accuracy of our method is tested by comparing our model predictions with results obtained from the Tomofast-X code (https://doi.org/10.5194/gmd-17-2325-2024) using a fine reference discretization of the topography with rectangular prisms. These tests are performed for the modeling of the effects of topography on gravity and magnetic responses over the geothermal system of Krafla, Iceland, considering both ground-based and airborne acquisitions.

## AS25-0349

# An approach for an interactive community-based data compilation for magnetic data—An example for Antarctica

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Magnetic data compilation on a global or continent-scale is a challenging endeavour due to the sourcing of data from many national programs and a diversity of surveys, hosted across numerous data centres and with varying data-access protocols. For Antarctica, the SCAR-ADMAP group has made huge progress to collate, coordinate and disseminate the magnetic data of Antarctica in a series of compilations.

Here, we present AIDMAP—the Antarctic Interactive Digital Magnetic Anomaly Project, a novel approach with a focus on the ability for researchers to access a live and interactive resource. Key changes from the traditional compilation approach is to be able to add new data when it is available, and for this to be realised in a compilation soon after data submission. For this, it is necessary to ease the burden of data processing, to define a consistent approach to data handling, and to accelerate the timeline from data-submission to incorporation into the compilation. Our approach therefore is founded on an automated data-processing workflow that can accommodate the wide variety of data submitted, with variable spacings, heights and times of collection, can tolerate incremental updates to the main product within a reasonable compute load, and can achieve results to a reasonable tolerance without requiring manual intervention. The core of the approach is an equivalent source inverse method, where step-wise resolution and data fit can be adjusted for both satellite and survey data. We present a roadmap for possible large-scale, even global, implementation.

## AS25-0494

# Unraveling the lithospheric magnetic field masked by the main field by estimating magnetization and crustal thickness with a statistical approach

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Detailed mapping of the Earth's lithospheric magnetic field provides key constraints on the composition, dynamics and history of the crust. This field can be modeled from satellite and near-surface measurements but structures with scales larger than about 2500 km are obscured by the magnetic signal from the core. Attempts have been made in the past to place statistical upper and lower bounds on the power of the hidden long wavelength part of the crustal field. More deterministic approaches relying on geophysical priors have also been used but those different efforts often led to contradicting results.

In this study, we propose a strategy based on regional spherical spectral analyzes of the WDMAM2.2. The data are analyzed over 6000 spherical caps. For each of them, a regional spatial spectrum is estimated, which is next used to constrain a regional statistical spectrum defined by three statistical parameters: the average magnetization, magnetic crustal thickness, and a power law. The best fit is achieved through a Monte Carlo Bayesian inversion, which provides joint probabilities between parameters. We next use this full statistical information to predict an ensemble of large-scale spherical harmonic lithospheric magnetic field models. We find a stochastic description of the hidden large-scale magnetic lithospheric field and we finally quantify how they contaminate the static and secular variation of the core field. This contamination is found to be significant between SH degrees 12 and 15 for the static core field and starting from SH degree 21 for the secular variation

## AS25-0549

# Macau Scientific Satellite-1 initial magnetic field model

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Eight months of vector magnetic field measurements from the Macau Scientific Satellite-1 (MSS-1), supplemented by higher latitude field intensity measurements from the Swarm satellites, are used to derive an MSS-1 Initial Field Model (MIFM). Robust root-mean-square misfits between MIFM and the three components of the MSS-1 vector data are found to be below 3.3 nT. MIFM agrees well with the CHAOS-7 field model and we find even better agreement with an identically parameterised model derived only from Swarm data. MSS-1 and Swarm vector data can moreover be fit simultaneously with only a small increase in misfit (by less than 0.2 nT). We show that both lithospheric anomalies and core surface field changes can be studied using MSS-1 data. With its fast coverage of local times MSS-1 is a valuable addition to the global geomagnetic observing system.

## AS25-0573

# The aeromagnetic signature of the Tajogaite Volcano on La Palma Island, Canary Archipelago

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Magnetic anomalies on the island of La Palma (Canary Islands) have recently been analysed through the construction of a 3D magnetic susceptibility model. The results of the regional model identified magnetic anomalies associated with dyke complexes in the central Taburiente area, to the north of the island. To the south, the most magnetic material of Cumbre Vieja is located beneath the main ridge. Additionally, low magnetic susceptibility on both sides of the ridge was interpreted as lateral structures related to hydrothermal alteration, as suggested by previous studies in other geophysical disciplines. To enhance the spatial resolution of the magnetic data for La Palma, we conducted a drone-based aeromagnetic survey, focusing on the Tajogaite volcano area. This technique enables a more detailed investigation of the fault system and potential magma conduits responsible for the 2021 Tajogaite eruption, thus deepening our understanding of volcanic dynamics in this region. The acquisition and integration of this new local information with the results from the regional 3D model offer a more accurate view of the geological structure in the region, opening new possibilities for geothermal and structural exploration on La Palma.

## AS25-0713

# Aeromagnetic survey on the territory of the Czech Republic and its contribution to the WDMAM

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Aeromagnetic mapping—measurement of the total intensity of the geomagnetic field—on the territory of the Czech Republic was started in the late 1950s. Since the early 1960s, measurements have been carried out along parallel tracks with a distance of 250 m. The measurements were completed in 2015. Given the long period over which the measurements were carried out, the relevant parameter is the anomalous value of the total intensity after subtracting the IGRF corresponding to the measurement period.

The provider of aeromagnetic data is currently the Czech Geological Survey, a state-funded organization under the Ministry of the Environment. Based on a mutual agreement, the CGS provided the Geophysical Institute with data with a spatial resolution of 1 x 1 km for research purposes. As a model case of using these data for future development of the WDMAM, we calculated the mean value of all points within a 5 km radius for each point of the 0.05° grid. Aeromagnetic data can also contribute to the quality of maps based on measurements from the national ground network.

## AS25-0753

# The World Digital Magnetic Anomaly Map version 2.2 (WDMAM-v2.2)

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The World Digital Magnetic Anomaly Map is an international initiative carried out under the auspices of the International Association of Geomagnetism and Aeronomy (IAGA) and the Commission for the Geological Map of the World (CGMW). A first version of the map has been published and distributed years ago (WDMAM v1; Korhonen et al., 2007) and the second version released for the IUGG in 2015. This latter version has been updated and released in 2023 as the version 2.1. After a review, it appeared that severe distortions of the anomaly field were visible around 60° latitude South. This problem has been corrected, and a new version of the map released as version 2.2. In this presentation, we will present the current status of the map, recall the technic used to merge together different data sets and point to few remaining problems and areas where data are still missing. We will then suggest a way forward to improve the map and present shortly examples of scientific applications.

## AS25-0771

# A cubed-sphere based method for global and regional modelling of the lithospheric magnetic field

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The Earth's magnetic field, which has been extensively observed from ground to satellite altitudes over several decades, originates from multiple sources, such as the core dynamo, the conductive mantle, the magnetized lithosphere, and the space current systems. Modelling of the lithospheric contribution plays an important role in the geophysical studies and industrial applications. In this report, we propose a new method for global and regional modelling of the lithospheric magnetic field based on the cubed-sphere. An equivalent dipole source method on a quasi-uniform cubed-sphere grid is employed in the forward modelling. The dipole directions are fixed according to a priori magnetization and the relative intensities are estimated by an inversion procedure of least-squares fitting with minimum model regularization. Several numerical tests are performed to validate the accuracy and efficiency of both forward modelling and inversion procedure. The proposed method is applied to the global and regional modelling based on the latest magnetic data from Swarm Alpha satellite and MSS-1 mission. The model results indicate that the proposed method works quite well for realistic satellite data and MSS-1 data is consistent with the Swarm data in terms of lithospheric field modelling.

## AS25-0778

# The contribution of the subducting slab to the magnetic signature of subduction zones

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In this study, we investigate the source of the magnetic field signal observed over most of Earth's subduction zones. For this, we model the induced magnetic field generated by the subducting slab of 13 subduction zones. Our forward models rely on our current understanding about the geometry, thermal state and composition of these subducting slabs. We compare our results to global magnetic field models based on spacecraft and near-surface magnetic field measurements. Based on this comparison, we find that the subducting slabs, in most cases in conjunction with the respective volcanic arc and/or upper plate, are the main sources of the observed magnetic anomaly. Our results do not preclude contribution from other sources, such as the mantle wedge, but suggest that their effect is secondary. Our results also indicate that the lack of magnetic signature above certain subduction zones is in some cases due to the zones' geometry and location, while in some others could be due to the masking by a thick accretionary prism. We point out, however, that while the Cascadia and part of the Central America subduction zones do not exhibit a magnetic signature, they do not clearly fit in either of these two categories. They require, therefore, further investigation.

## AS25-1040

# Magnetic anomalies and the Continent-Ocean Boundary

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The definition of the Continent-Ocean Boundary (COB) at continental passive margins is, in theory, very simple: the COB is the location where continental crust ends and oceanic crust starts, i.e. the place where seafloor spreading initiated between two rifted and finally broken continents. Practically the interpretation of the COB has proven much more difficult. At volcanic margins, abundant volcanism predates the breakup and obscures the COB with thick volcanic accumulations characterized by seaward-dipping reflectors and underplated magmatic bodies. At non-volcanic margins, detachment faulting and mantle denudation often create ambiguous areas where there is no more continental crust but no oceanic magmatism yet. The current paradigm considers that the first clear marine magnetic anomalies unambiguously mark the COB, i.e. the crust including these anomalies and beyond is clearly oceanic. However, many areas bounding continental shelves bear all characteristics of oceanic crust, except clear magnetic anomalies. Our recent works in the Red Sea and the Gulf of Mexico, as well as other results from the South Atlantic margins and the Andaman Sea, suggest that abundant sediments and, in particular, evaporites in nascent ocean basins hinder the formation of an extrusive basalt layer and therefore hide the onset of seafloor spreading as usually depicted from marine magnetic anomalies. In these and other areas, the actual COB lies landward with respect to the first unambiguous magnetic anomaly.

## AS25-1073

# World Digital Magnetic Anomaly (WDMAM) version 2.2 released

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The World Digital Magnetic Anomaly Map is prepared under the auspices of IAGA and the CGMW (Commission for the Geological Map of the World) of UNESCO. A first version was released in 2007 (Korhonen et al., map CGMW, 2007), and a second one in 2015 (Dyment et al., EPSL, 2015; Lesur et al., Solid Earth, 2016) with the mandate to update the version 2.0 using the same methodology when the availability of new data would make it necessary. WDMAM version 2.1, compiled at 5 km interval, at 5 km altitude above the continents and at sea-level over the oceans, included new data compilations over Brazil, Russia, Antarctica, the Caribbean and Gulf of Mexico, East and Southeast Asia, and the Oceans but suffered a bug over Antarctica due to a mistake in projecting the ADMAP data to geographic coordinates. This problem has now been corrected and the new WDMAM version 2.2 is now available on web site wdmam.org.

## AS25-1399

# Curie depth analysis unveils contrasting geothermal heat flux provinces beneath Antarctic subglacial lake districts

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A new Antarctic-wide aeromagnetic anomaly compilation, conformed at long wavelengths with SWARM satellite magnetic data provides a key new tool to re-assess Antarctic geothermal heat flux (GHF) heterogeneity and its influence on subglacial lake districts hidden beneath Antarctic ice sheets. We applied Curie Depth Point (CDP) estimation using the centroid, modified centroid and fractal/defractal approaches and compared the results with crustal and lithosphere thickness as derived from seismological, airborne and satellite gravity modelling and with effective elastic thickness estimates. We also considered empirical estimates of GHF derived from seismology and recent models of intracrustal heat production from gravity inversion.

We found elevated GHF in the West Antarctic Rift System (WARS) beneath the rapidly changing Thwaites (THW) and Pine Island sectors of the West Antarctic Ice Sheet (WAIS) and also beneath the active subglacial lake districts that underlie the fast-flowing ice streams of the Ross Sea Embayment.

In East Antarctica, elevated GHF occurs beneath active lake clusters of the Byrd glacier catchment, but the lake districts of the northern Wilkes Subglacial Basin (WSB) exhibit lower GHF. Surprisingly elevated GHF characterises the Dome C and Dome A subglacial lake districts, reflecting either high heat producing Precambrian basement or intraplate fault reactivation. Elevated GHF also occurs in Dronning Maud Land where subglacial lakes also occur benath relatively less thick parts of the East Antarctic Ice Sheet and may stem from lithosphere thinning processes after Gondwana assembly.

# A07 Geomagnetic Observations, Indices and Products for Space Science, Space Weather and Space Climate Applications

## AS25-0034

## Magnetospheric and ionospheric currents responses to the intense geomagnetic storm on 10–12 May 2024

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Currents in the space are the main driver to cause external variations of the Earth's magnetic field, especially during magnetic disturbed periods. In this study, we performed a detailed analysis of the magnetospheric and ionospheric currents responses to the intense geomagnetic storm on 10–12 May 2024. Combined magnetic measurements from groundbased stations, ESA's Swarm, Macau Science Satellite (MSS), have been used. In the ionosphere, Extreme eastward and westward EEJ values, reaching 300 mA/m and -400 mA/m at both dawn and noon sector have been observed during the storm main and recovery phases, respectively. Such values have never been observed during the past 11-year flying period of Swarm. The zonal currents showed quite different behaviors at different magnetic local time sectors. Around noon sector, the zonal currents directed mainly eastward during quiet and storm periods, while in the dawn and dusk sectors, prominent eastward and westward currents have been observed immediately after the sudden storm commencement and persisted for the rest one and a half days. In the magnetosphere, the ring currents showed strong dawn-dusk asymmetry. Our results indicated compared to the near-polar orbital satellites, the MSS, with its low inclination orbit, has great advantage to reflect the magnetic local time variations of the space currents, which will also be helpful for the IGRF modeling.

## AS25-0068

# The great solar and geomagnetic storm in May 2024: A data overview

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In May 2024, the scientific community experienced and observed a series of intense solar eruptions that resulted in an great geomagnetic storm and auroral extension. This solar storm is one of the greatest storms in the last decades and offered numerous unique observations. This context highlighted the need to document and quantify each of their aspects. This presentation mainly focuses on their quantification. This presentation quickly review the data we got for this storm on the basis of Hayakawa et al. (2025, ApJ, 979, 49), such as those for the evolutions and eruptions of the AR 13664, coronal mass ejections, magnetospheric impact, cosmic ray variations, geomagnetic disturbance, auroral activity, and ionospheric disturbance. This presentation also aims at contextualising this storm within the extreme solar/geomagnetic storms in history as well.

## AS25-0071

# A new observatory-based model for forecasting geomagnetic Kp and Hpo indices using geomagnetic data

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Geomagnetic activity indices, such as Kp and the recently introduced Hpo indices, are essential for monitoring and forecasting space weather, as they provide a global measure of geomagnetic disturbances driven by solar activity. These indices are calculated from data collected from 13 geomagnetic observatories worldwide. Accurate forecasting is crucial, as geomagnetic storms can significantly impact technological systems, including satellite operations, power grids, and communication networks, as well as human activities in Earth's atmosphere and near-Earth space. We introduce a novel forecasting model where the geomagnetic index is obtained from predictions of data from the individual observatories rather than forecasts of the precomputed global indices. Unlike traditional models that directly predict an index, our approach considers each observatory separately in the forecasting process and thus takes into account diverse physical effects at individual locations. This methodology ensures that the forecasted indices remain consistent with the fundamental principles used in their original derivation. We demonstrate the performance of the model for the Kp index along with the Hpo indices, Hp60 and Hp30, which provide high-resolution (hourly and half-hourly) measurements of planetary geomagnetic disturbances similar to the 3-hourly Kp index but without the upper limit of 9. The model demonstrates good agreement, accurately capturing trends and overall behaviour, even with sparse solar wind data. Results indicate that this methodology holds significant promise for improving the prediction of geomagnetic indices. Moreover, the framework is adaptable for forecasting other indices derived from global observatory networks, such as Dst and AE.

## AS25-0146

# Assessing geomagnetically induced currents models using differential magnetometer data and transfer function analysis

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This study investigates geomagnetically induced currents (GICs) and their effects on power grids, with a focus on the Spanish network. GICs arise from solar activity that disturbs Earth's magnetosphere and ionosphere, generating magnetic fluctuations that induce currents in grounded infrastructures like power grids. We detail the implementation of a network of Differential Magnetometer Method (DMM) stations to indirectly measure GICs along power transmission lines. This includes an overview of station deployment and the logistical challenges of maintaining them in remote areas.

We validate our GIC models using measurements from these stations, comparing the results with model predictions. The study highlights that accurate GIC forecasting depends on precise modeling of subsurface resistivity and reliable geomagnetic field data. Case studies are presented to illustrate varying levels of agreement between observed and modeled GICs during geomagnetic storms. Additionally, we explore the development of transfer functions to reconstruct natural magnetic field variations at DMM stations using data from geomagnetic observatories. This approach allows for the reduction of DMM magnetometers or even the cessation of recordings at remote sites while still achieving accurate GIC estimates.

## AS25-0149

# ESA's VirES service for accessing and analysing data from Swarm and beyond

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The VirES service[1] has been developed to make Swarm products[2] accessible to programmers and non-programmers alike. Web services provide robust access to both data and models, which are coupled to a graphical interface for easy exploration and visualisation, as well as Python tooling to support community-developed tools and processing options. We are also able to integrate with other data systems through adoption of the Heliophysics API (HAPI)[3].

While the service was originally developed to serve Swarm products, we also provide access to ground magnetic observatory data derived from INTERMAGNET, as well as Swarm "multimission" products derived from other spacecraft. Ready-to-run Jupyter notebooks[4] provide accessible data recipes, backed by a JupyterHub furnished with domain-relevant Python packages.

Building upon robust data access via VirES and HAPI, Swarm DISC (Swarm Data, Innovation, and Science Cluster) is also developing the SwarmPAL Python package[5] to facilitate higher-level analysis. Overall, we aim to produce a sustainable ecosystem of tools and services, which together support accessibility, interoperability, open science, and cloud-based processing. All services are available freely to all, and the software is developed openly on GitHub[6,7].

The work presented is the result of many partners across Swarm DISC.

[1] https://vires.services
[2] https://swarmhandbook.earth.esa.int
[3] https://hapi-server.org
[4] https://notebooks.vires.services
[5] https://swarmpal.readthedocs.io
[6] https://github.com/ESA-VirES
[7] https://github.com/Swarm-DISC

## AS25-0151

# Revolutionizing geomagnetic data for space weather monitoring in New Zealand

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In Aotearoa New Zealand (NZ), geomagnetic waveform data has been recorded since 1916. The Eyrewell Geomagnetic Observatory (EYR), a member of INTERMAGNET since 1994, has contributed to the global Kp index from its early years. Recently, however, this data has gained greater prominence in space weather research and monitoring.

Historical magnetograms, recorded on photographic paper from 1916 to 1991, provide valuable insights for improving statistical models that predict extreme geomagnetic storm scenarios in NZ. As part of the "Solar Tsunamis" research programme, we have digitized key portions of this dataset, producing 1-minute resolution data for major storms since 1951. We will present the 4 August 1972 storm as an example.

Additionally, we have developed a real-time magnetic field monitoring tool for EYR, which delivers rate-of-change information within 5-minute latency to support space weather monitoring. This tool leverages correlations between Geomagnetically Induced Currents (GICs) and magnetic field measurements and powers a dashboard (https://www.geonet.org.nz/data/geomag/dashboard) and API, providing publicly available 1-minute and 1-second resolution data streams.

The Solar Tsunamis programme established the Magnetometer Array for New Zealand Aotearoa (MANA), expanding the magnetometer network with five research sites. The 10–12 May 2024 "Gannon" geomagnetic storm, which exhibited a maximum rate of change of 320 nT/min at EYR, demonstrated NZ's enhanced capacity to capture and analyze geomagnetic events nationwide.

## AS25-0158

# What can we learn from the properties of the solar wind parameters during the geomagnetic storms on 2000 October 5?

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We study the relationship between the variation speed of the ring current during the main phases of the two geomagnetic storms and the corresponding solar wind parameters occurred on 2000 October 5. The z-component interplanetary magnetic field (IMF) was oriented southward during two separate periods on October 5, 2000. The first period commenced at 03:37 UT and ended at 06:24 UT (hereafter period1). The second period began at 10:55 UT and terminated at 12:32 UT (hereafter period2). We conducted an analysis of solar wind parameters and calculated the averaged change rate of the ring current, represented by $-\Delta SYM{-}H/\Delta t$, for both period1 and period2. Our analysis revealed that the $-\Delta SYM{-}H/\Delta t$ value during period2 exceeded that of period1, suggesting a faster average change rate of the ring current in period2 compared to period1. However, despite the averaged southward IMF (denoted as $Bs$), the maximum $Bs$, and the averaged solar wind electric field $Ey$ being greater during period1 than period2, the $-\Delta SYM{-}H/\Delta t$ was not solely determined by the southward IMF or the solar wind electric field. Additionally, we found that the solar wind dynamic pressure during period2 was higher than during period1. This suggests that the rate of change of the ring current is not only influenced by the solar wind electric field but is also significantly affected by the solar wind dynamic pressure, indicating that the dynamic pressure plays a crucial role in the rate of change of the ring current, alongside the solar wind electric field.

## AS25-0220

# Long-term homogeneity of the Sudden Commencement (SSC & SI) lists

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Magnetic storms are the most dramatic events in the near-Earth environment. They produce large variations in the magnetic field measured by ground magnetic observatories. Magnetic storms are mainly related to solar wind structures. Roughly one half of magnetic storms are preceded by sudden increases in the horizontal component of the magnetic field. Called Storm Sudden Commencements (SSC), these remarkable events are of great interest because, among others, they cause relevant space weather events, e.g. when producing geomagnetically induced currents in long grounded conductors. In fact, in low and middle latitudes, the maximum values of the geoelectric field generated at the Earth's surface often occur coincident with the abrupt onset of the storms.

SC event lists date back to 1868, thus providing invaluable information about interplanetary conditions over the long-term. Since 1975, the Service of Rapid Magnetic Variations is officially responsible for the maintenance and consistency of the SC list endorsed by International Association of Geomagnetism and Aeronomy (IAGA). The service pursues the collection of information from ground observatory magnetograms and the compilation of the IAGA-endorsed SC list, offering a time series that is excellent for Sun-Earth relationship studies.

In this presentation, we will discuss the homogeneity of the series and analyse the effects of the historical evolution of the definition and the different methodologies of the detection that have been introduced over the time when producing the SSC and SI (Sudden Impulse) lists. We will also discuss the possible consequences of these changes to the homogeneity of these series.

## AS25-0366

# Solar wind driven SuperMAG statistical equivalent current model

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We present a Solar Wind-driven SuperMAG statistical Equivalent Current model (SW-SMEC), which describes ionospheric equivalent currents in the Northern Hemisphere. The model is based on SuperMAG ground magnetometer data from 1997–2008 and predicts equivalent currents as a function of the interplanetary magnetic field (IMF) clock angle, solar wind electric field magnitude, and Earth's dipole tilt. The currents predicted by SW-SMEC exhibit well-known characteristics, including a strong dependence on the IMF north-south component and solar wind electric field. Equivalent currents are stronger for a positive IMF dawn-dusk component than for a negative one, and they are more intense in summer than in winter. We tested SW-SMEC in two case studies of geomagnetic storms, driven by a high-speed stream (HSS) and an interplanetary coronal mass ejection (ICME), respectively. The model succeeds in reproducing the main features of both HSS- and ICME-driven storms with comparable accuracy, as estimated by comparison with SuperMAG measurements. The accuracy is highest during the storm's main phase and lowest during the initial phase. A statistical study of 227 storms during solar cycle 24, covering different storm drivers, indicates that SW-SMEC performs better for ICME-driven storms than for HSS-driven storms. It also shows that the optimal solar wind integration time for the model is typically 100 min, although it varies depending on the storm phase or driver.

## AS25-0432

# Seasonal and universal time variations of Pi2 activity deduced from the Wp index

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Seasonal and universal-time (UT) variations in geomagnetic activities have been examined by various studies. These studies showed that geomagnetic activity tend to be higher during equinox seasons than during solstice seasons. There are two well-known explanations of this seasonal variation: the Russell-McPherron effect and the equinoctial effect. The Russell-McPherron effect is derived from the statistical property of the solar wind magnetic field in the GSM coordinates. On the other hand, the equinoctial effect is due to the seasonal and UT variation of the direction of the Earth's dipole axis. We examined the cause of the seasonal and UT variations using a machine-learning model. Our recent study trained a machine-learning model called echo state network to represent the response of Pi2 occurrence rate to various solar wind conditions, seasons, and UT conditions. In our model, the Russell-McPherron effect is learned as a response to the solar wind variation, while the equinoctial effect is learned as the seasonal and UT variation independent of the solar wind variations. We examine the contribution of each effect to Pi2 occurrence frequency by inputting various synthetic data into the model. The result shows that the seasonal and UT variations of Pi2 occurrence frequency are mostly attributed to the equinoctial effect. The pattern of the UT variations seems to also contain another effect due to the UT dependence of the location of geomagnetic observatories used for calculating the Wp index.

## AS25-0617

# On the estimation and prediction of ground level magnetic field perturbation from observatory data

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The time derivative of the horizontal ground-level magnetic field is an indicator of the potential presence of geomagnetically induced currents (GICs) flowing through grounded infrastructure in a given region. As GICs are potentially hazardous to critical technical infrastructure, it provides incentive to estimate this ground-level magnetic field diagnostic. The horizontal time derivative can be calculated from geomagnetic observatory measurements, which are generally recorded at a 1 minute cadence. However, there are several different methods of calculating this time derivative, and it is important to recognise that they can result in significantly different values. One method is based on temporally-consecutive differences of the horizontal field intensity while the other also takes into account the change of direction between these two times. The difference between the methods can exceed 100 nT for subauroral observatories, which occurs in addition to a smaller measurable difference close to the agonic line caused by a digitising resolution of 0.1 nT in observatory measurements. We suggest that the correct method using directional change should be incorporated within any calculation of the time derivative of the horizontal ground-level magnetic field, and we comment on the potential benefit of improving resolution in the recorded magnetic field data at geomagnetic observatories.

## AS25-0636

# International Service of Geomagnetic Indices: update of its roadmap

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The International Service of Geomagnetic Indices (ISGI) is in charge of the elaboration, validation, dissemination and stewardship of IAGA-endorsed data-products, i.e. geomagnetic indices and lists of remarkable magnetic events.

Six International Institutes collaborate in the frame of ISGI. These ISGI-Collaborating Institutes derive and provide the reference data-products relying onto reports and measurements from worldwide ground magnetic observatories. ISGI has to meet the state of art in data management but also, for different e-infrastructures, the needs of both “solid earth” and “sun-earth relationships” scientific communities and beyond.

We present here the updates of ISGI’s roadmap.

## AS25-0649

# Determining a Magnetic Local Quiet Day via Data Assimilation: a Machine Learning Approach

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Quiet Days (QDs) play a crucial role in baseline removal processes, particularly in eliminating diurnal variations. This project aims to develop a local QD selection process based on the criteria established by van de Kamp (2013) for identifying Local QDs (LQD). However, a selected LQD may occasionally exhibit behavior that deviates from the other selected LQDs within the same month, even if its magnetic data variability is sufficiently low,as determined through empirical testing. To address this issue, we explore correlations between variations in ionosonde parameters from the E and F regions and magnetic data during LQDs. To improve the selection process, we propose a data assimilation (DA)technique combined with a machine learning approach that integrates magnetometer data and ionosonde parameters to estimate Local QDs within a specified time window. This approach was evaluated using data from observatories in Mexico and Peru. The results were compared with international quiet days and identified events to assess its effectiveness.

## AS25-0679

# Magnetic field observations from the May and October 2024 geomagnetic storms in New Zealand using the MANA magnetometer array

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The Magnetometer Array for Aotearoa New Zealand or MANA is an array of five variometer sites across New Zealand, whose installation was completed in 2023. The network complements the existing INTERMAGNET Eyrewell geomagnetic observatory, enhancing our spatial resolution of the geomagnetic field to approximately 200 km. An innovative approach was used to build the network. Sites feature Raspberry Pi computers, 4G wireless modems for communications, solar panels and batteries for power where needed, while still using high quality magnetometers. The network streams 130 Hz cadence data in real time, which we use to monitor geomagnetic field conditions (https://solartsunamis.otago.ac.nz/mana/data/). As well as presenting technical details on the network, we will report on magnetic field observations from 2024, in terms of H, dH/dt and H30 indices, a recent upgrade to K indices from GFZ. Most notably, this includes the 10–12 May 2024 "Gannon" storm, which was locally the largest geomagnetic storm in terms of dH/dt since before digital records began (pre-1989). We will also present measurements from the weaker but still significant 10–12 October 2024 storm, whose impact was locally more variable across the islands of New Zealand.

## AS25-0687

# Local geomagnetic disturbances and global indices: a comparison for Southern Europe

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Geomagnetic storms pose a threat to electrical infrastructure and communications systems, accurate knowledge of geomagnetic disturbance in a given region is crucial to mitigate the effects of the storm and protect human activity. We compared the local disturbance of the geomagnetic field measured at six Southern European observatories (geomagnetic latitudes ranging from 41 N to 50 N) during the last 30 years with the variations of the Dst (1 h data) and SYM-H (1 min data) global indices. We found that during this time interval the average difference between the local and the global parameters was below +10 nT for all the observatories and for both Dst and SYM-H, but increased to about +30 nT for mild storms and to about +50 nT for the most intense storms. Positive deviation in this analysis means an overestimation of the average disturbance by the global indices. However, for the 1-minute resolution data the differences between global indices and global disturbances featured in all observatories are much higher (in absolute) than for the 1-hour data (about -600 nT vs. -100 nT). Moreover, the negative deviation indicates that the fast minute variations in the local disturbance are not captured by SYM-H nor Dst. Thus, while Dst and SYM-H showed an average overestimation of the disturbance during storms, they also missed significant drops in the local field, which suggests that the quantification of the severity of geomagnetic storm requires more analysis than only the characterization given by the global indices.

## AS25-0719

# Validating the Differential Magnetometer Method for GIC observations during a transformer stress test at Haywards substation, Wellington, New Zealand

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During increased solar activity, large fluctuations in the geomagnetic field can lead to strong geomagnetically induced currents (GICs) with the potential to damage grounded infrastructure such as high voltage (HV) power transformers. GICs are often directly monitored in transformers at substations using Hall probes, but such data are rarely made available to researchers to validate GIC models. Therefore, the differential magnetometer method (DMM) has been deployed in many countries to measure the indirect GIC signal flowing in power lines. The DMM utilizes two three-component fluxgate magnetometers, one positioned directly under the power line and a second system further away, to infer the additional direct current (DC) flowing in the HV line due to GICs. In this study, we analyse DMM observations from a transformer stress test at Haywards substation near Wellington, New Zealand as part of the Solar Tsunamis project. In this unique setup, 600 A of current from a HVDC line was deliberately injected into the ground to test the flow back into the local AC network. With this test it is possible to directly compare measured DMM data collected under two HV lines connected to the substation during the stress test with transformer GIC data. We show that DMM data measured along the lines accurately captures the direct current fluctuations measured in the Haywards substation transformers.

## AS25-0741

# A statistical study on the relative role of ICME parameters on the SYM/H index of associated geomagnetic storms

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Understanding the effects of the potential inputs used by Dst forecast models is crucial to improving predictions of geomagnetic storm intensity and profile. Since ICMEs are among the most frequent and intense causes of geomagnetic storms, we study the impact of ICME parameters on the SYM/H index, a high resolution indicator of the intensity of a geomagnetic disturbance. We select intense geomagnetic events caused by ICMEs with Dst <= -100 nT across three different solar cycles (SC23-SC25). We aim to understand the impact of the solar wind parameters i.e. the southward component of the magnetic field, plasma flow speed and proton density on the SYM/H index. Since ICMEs have two different storm drivers—the magnetic sheath and the magnetic cloud, we also aim to understand the relative impact they have on the SYM/H index. We define CI, the "storm coupling integral"—a metric obtained by integrating a solar wind coupling function over a geoeffective time interval and use it to identify the primary storm driver. We also try to understand the impact on SYM/H with respect to the CI. Our analysis enables us to connect the SYM/H index with different ICME storm drivers as well as the solar wind input parameters used by Dst forecast models and provides a direction to further refine their prediction capabilities.

## AS25-0746

# Analysis of Equatorial Geomagnetic Field Variations in Thailand during Intense Geomagnetic Storms of Solar Cycles 24 and 25

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Geomagnetic field observations are crucial in monitoring space weather and understanding equatorial and low-latitude ionospheric electrodynamics, particularly during geomagnetic storms. Severe geomagnetic storms affect ionospheric and geomagnetic dynamics, including the equatorial ionization anomaly (EIA) and equatorial plasma bubbles (EPBs), in equatorial regions, such as Thailand. These variations result from a combination of ionospheric currents and the penetration of storm-time electric fields, affecting satellite communications and navigation systems, and power gride.

In this study, we analyze equatorial geomagnetic field variations using magnetometer data from two equatorial stations in Thailand: Phuket and Songkhla, during geomagnetic storms and quiet periods in Solar Cycles 24 and 25. A non-parametric machine learning approach, Singular Spectrum Analysis (SSA), is applied to decompose the geomagnetic field into its elementary components, enabling a detailed analysis of both storm-time disturbances and quiet-time characteristics. We examine the correlation between the reconstructed geomagnetic variations, derived from different combinations of components, and interplanetary geophysical parameters as well as equatorial ionospheric TEC. During the May 2024 storm event, our results clearly distinguish different components of geomagnetic field variations driven by interplanetary and ionospheric parameters, based on correlation coefficients between the reconstructed field components and other parameters. The findings contribute to a better understanding of how storm-induced electric fields and ionospheric currents drive geomagnetic variations at equatorial and low latitudes.

### Acknowledgement

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## AS25-0797

# Prediction of coronal mass ejection geo-effectiveness using Solar Orbiter as a far upstream solar wind monitor in real-time

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Coronal mass ejections (CMEs) are the main drivers of severe space weather at Earth which can cause significant disruption to both satellite and ground systems, necessitating accurate predictions for timely mitigation. The complicated nature of the processes affecting CMEs as they propagate makes understanding and predicting their physical properties and global structure a challenging task, from both a fundamental and practical space weather perspective. Current challenges lie in forecasting CME arrival time and magnetic structure prior to Earth arrival, closely related to our ability to directly measure their magnetic field configuration between the Sun and 1 AU, which is critical for assessing their geo-effectiveness.

Recent opportunities provided by Solar Orbiter crossing the Sun-Earth line have allowed us to monitor upstream solar wind conditions in real-time. On 23 March 2024, Solar Orbiter observed a fast CME whilst located upstream of Earth at 0.39 AU. It provided observations of the CME magnetic field vector in real time, with a lead time of over one day before Earth impact. We present the analysis performed that led to the first real-time prediction of the geomagnetic magnitude of a severe geomagnetic storm (minimum Dst -130 nT) with sufficient accuracy and lead time. Our results demonstrate the necessity of future real-time upstream solar wind monitors towards providing accurate and timely predictions of space weather effects.

## AS25-0956

# Statistical analysis of geomagnetic Sudden Commencements at middle and low latitudes

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We performed a statistical analysis of geomagnetic sudden commencements using geomagnetic field data from observatories at middle and low latitudes. In particular, the observatories are located in the Italian territory and in the southern hemisphere including the area broadly corresponding to the South Atlantic Magnetic Anomaly. We investigated the dependence of the ground steady response to solar wind pressure pulses on local time and latitude. In the Italian sector, the response shows lower values in the morning sector with respect to the afternoon sector and its amplitude increases with increasing latitude. A different response is found at the lowest latitude observatories, with maximum amplitude in the pre-noon sector and a secondary maximum in the pre-midnight sector. We also investigated the possible effect of the orientation of the north-south component of the interplanetary magnetic field.

## AS25-1097

# Comparative Analysis of the May and October 2024 Geomagnetic Storms

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This study utilizes data from over 100 globally distributed magnetic observatories to provide a comprehensive assessment of the ground-level impacts of two intense geomagnetic storms that occurred in May and October 2024. By analyzing both the horizontal and vertical components of the magnetic field and the rate of change of the horizontal intensity (dH/dt), a key proxy for geomagnetically induced currents (GICs), we characterize the storm-time dynamics.

Global and polar maps reveal a pronounced equatorward expansion of auroral electrojets, asymmetric ring current dynamics, and significant regional variations in geomagnetic responses. Rapid dH/dt variations highlight areas potentially at risk from GIC-related impacts on technological systems. A comparative analysis of the two events underscores differences in storm evolution and intensity.

The results contribute to a deeper understanding of extreme geomagnetic disturbances and offer valuable input for improving space weather forecasting models and risk mitigation strategies.

This study is supported by the Space-It Up project of the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.0—CUP n. I53D24000060005.

## AS25-1105

# Quantifying the Efficiency of Viscous Interaction during Intense Northward IMF Bz events of 23- 24 Solar Cycles

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The solar wind-magnetosphere coupling occurs primarily via two physical processes that are magnetic reconnection and viscous interaction. The viscous interaction is generated by a convective motion that is produced by the anti-sunward dragging of plasma inside the magnetopause by the plasma flowing in the magnetosheath, creating a return flow deeper inside the magnetosphere. The ionospheric electric field in the nonrotating Earth's frame is formed when the viscous circulation pattern is mapped into the ionosphere via magnetic field lines. There are several studies showing the contribution of viscous interaction in the energy budget of the magnetosphere. However, how this changes with the solar cycle is yet to be well understood. The present study examines specifically selected large northward IMF Bz events during two solar cycles (23 and 24) with northward IMF Bz (>10 nT) for a long duration of time (> 3 hours) to minimize the effects of magnetic reconnection at sub-solar point. The quantitative estimates of the viscous interaction are performed to evaluate its relative importance and variation of efficiency in terms of energy inputs into the magnetosphere with the solar cycles.

## AS25-1180

# Extreme space weather event of May 2024: Geomagnetic and ionospheric disturbances

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The G5-Level Gannon Geomagnetic Superstorm of May 10–11, 2024, ranks among the most intense space weather events in recent decades, significantly affecting Earth's magnetosphere and ionosphere. This study integrates ground-based magnetometer data and ionospheric observations to analyze the geomagnetic and ionospheric responses, with a particular focus on mid-latitude regions.

The storm was triggered by interplanetary coronal mass ejections (ICMEs) from active region AR 13664, pushing the Kp index to its maximum value of 9. Geomagnetic analyses from mid-latitude observatories (30°–60° N) reveal sudden storm commencements (SSCs), prolonged negative excursions in the Disturbance Storm-Time (Dst) index, and asymmetric geomagnetic disturbances indicative of intensified auroral electrojet activity. Concurrently, ionospheric data over Europe show significant perturbations, with fluctuations propagating from high to low latitudes. These disturbances correlate with key geomagnetic parameters, including the Sym-H index, interplanetary magnetic field (IMF), and interplanetary electric field (IEFy).

The findings underscore the strong coupling between the magnetosphere and ionosphere during extreme geomagnetic activity and highlight the importance of continuous space weather monitoring. Additionally, they emphasize the crucial role of mid-latitude observatories in capturing geomagnetic variations beyond traditional auroral zones, offering valuable insights into space weather dynamics and its implications for technological infrastructure.

## AS25-1231

# Centennial occurrence of CME and HSS storms: Evidence for differences between the growth and decay phase of the Modern Maximum

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We study magnetic storms during the 120-year time interval (1903–2023), which covers the whole Modern Maximum (MM, the latest Gleissberg cycle) of solar activity. Storms are mainly driven by coronal mass ejections (CME) and high-speed solar wind streams with related stream interaction regions (HSS/SIR). CME occurrence closely follows sunspots, the emergence of new strong magnetic flux, while HSS/SIR occurrence depends on the global structure of solar corona, in particular coronal holes, which is determined by the evolution of solar active regions (e.g. plages).

Studying different types of storms during the last century can yield information on the occurrence of CMEs and HSSs both in the growth phase and in the decay phase of the Modern Maximum and, thereby, on the evolution of the Sun during this period of exceptional activity.

We find, e.g., that the CME storms were relatively more frequent in the MM growth phase than in the decay phase. This is in agreement with the recent finding of the change in the mutual relation of sunspots and plages so that sunspots are relatively more frequent in the growth than the decay phase of the MM.

We discuss these results in view of better understanding the solar centennial evolution and the long-term occurrence of CME and HSS/SIR storms at the Earth. We also note on the implications of these findings on the stellar evolution of the Sun and Sun-like stars.

## AS25-1331

# Metallurgy study on the performance of experimental permalloy for fluxgate magnetometers used in space flight applications

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Fluxgate Magnetometers historically have flown with ferromagnetic cores of a certain high permeability alloy (permalloy). Recent experiments provide evidence that a new permalloy in a different alloy regime perform better than what is current used. Updating this aspect of the instrument is crucial for less power consumption, better magnetic sensing, and less magnetic noise produced by the fluxgate magnetometer. Magnetometers provide the information on the interplanetary medium fields and are used to study the Interplanetary Magnetic Field due to the instrument's low-noise and high sensitivity to DC and low frequency AC magnetic field changes. This work details the creation of the permalloy ingots, their transformation into ferromagnetic cores, and characterization of coercivity, saturation, permeability, and magnetization range. The leading experimental permalloy will be used in a fluxgate magnetometer on an upcoming sounding rocket mission.

## AS25-1356

# Dynamical complexity in Swarm-derived storm and substorm indices and ground-based Geomagnetically Induced Current indices using information theory

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In 2025, the ESA Swarm constellation mission will celebrate 12 years in orbit, offering one of the best ever surveys of the ionosphere. Among its achievements, it has been recently demonstrated that Swarm data can be used to derive space-based geomagnetic activity indices, similar to the standard ground-based geomagnetic indices monitoring magnetic storm and magnetospheric substorm activity. The Geomagnetically Induced Current (GIC) index is a proxy of the ground geoelectric field derived solely from geomagnetic field data. Information theory can be used to shed light on the dynamics of complex systems, such as the coupled solar wind–magnetosphere–ionosphere–Earth system. We performed entropy analysis of the Swarm-based SYM-H and AE indices, as well as GIC activity indices at middle-latitude European observatories around the Mother's Day (or Gannon) May 2024 superintense storm. We found that the GIC index values were generally higher for the May 2024 storm in comparison to the St. Patrick's March 2015 intense storm, indicating elevated risk levels. Furthermore, the entropy values of the Swarm SYM-H and AE, as well as GIC indices were higher in the time interval before the storm than during the storm, indicating transition from a system with lower organization to one with higher organization. These findings, including the temporal dynamics of the entropy values and GIC indices, highlight the potential of this method to reveal pre-storm susceptibility and relaxation processes. This study not only adds to the knowledge of geomagnetic disturbances but also provides valuable practical implications for space weather forecasting and geospatial risk assessment.

## AS25-1357

# Empirical Modeling of Geomagnetic Storms

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We will present results from an interdisciplinary project seeking to combine ground-based and satellite data, physics-based modeling with the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE GCM), and three-dimensional (3D) modeling of induced geo-electric fields to map ionospheric current systems and ultimately, Geomagnetically Induced Currents (GICs). The first step in our modeling approach uses frequency domain principal components analysis (PCA) of ground-based data to decompose magnetometer array data as a sum over a modest number (~25) of temporal/spatial mode products. We focus on the Northern polar region, using one minute data obtained from SuperMag for geomagnetically active times over the period 2013–2018. Temporally and spatially continuous aps of external source currents are then derived from the sparsely sampled ground-data spatial modes by fitting to two-dimensional (external potential) basis functions derived from a similar PCA of TIE GCM outputs, allowing for induction. Induced fields are modeled with a prior 1D+thin sheet model, with empirical corrections for 3D induced fields derived as part of the fitting process. The combination of temporal and (interpolated) spatial modes yields data and physics constrained models of storm-time equivalent ionospheric current systems. We are extending this work to use 3D basis functions (also obtained from PCA of TIEGCM outputs) and fitting satellite data from the Swarm constellation. The source fields are used to force 3D electromagnetic induction models, and to study electric fields induced in a realistic Earth conductivity model by realistic storm-time source fields.

# A08 Space Weather and Electrodynamics of the Ionosphere and Atmosphere in the Polar Regions

## AS25-0126
## Five extreme storm time events: Testing our understanding

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We show 5 different extreme events as identified in ground based magnetometer data. Abrupt and extreme variations of the ground level magnetic field is related to ground induced currents and with disruptive space weather related societal implications. The underlying processes resulting in these events is a focus of the field due to at least three reasons: They serve as a test of our understanding of the underlying physics, they serve as an excellent means to test the capabilities of simulations, and, they are important for identifying societal impacts. In this paper we present 5 different extreme events, all occurring during storm time conditions. The characteristics of these events are different: ranging from very localized to global and occurring on the nightside as well as dayside. The underlying processes are likewise different, including externally driven by the solar wind and internal plasma sheet processes. Using standard indices such as AL/SML is not sufficient to identify, classify and study these events since two different events can produce essentially identical traces but be due to completely different processes. We use a long list of ground based and space borne assets to characteristics the events and to educate our interpretation of why they occurred. Three of the five events occurred during the May 2024 storm.

## AS25-0205

# First steps of the AGATA Scientific Research Programme

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AGATA (Antarctic Geospace and Atmosphere ReseArch) is a Scientific Research Programme (SRP) of the Scientific Committee on Antarctic Research (SCAR). AGATA SRP has been approved as Scientific Research Programme by the SCAR Delegates Meeting in August 2024 with the start of activities in January 2025.

AGATA SRP addresses the following outstanding questions:

- How are different atmospheric layers coupled in the polar regions?
- How does the high latitude upper polar atmosphere respond to increased geomagnetic activity, including energy transfer from space?
- How does the whole polar atmosphere impact short- and long-term climate variations?

To understand the global context, the AGATA SRP will be set in the interhemispheric perspective: it will consider the Antarctic and Arctic atmosphere to understand the differences and similarities between the polar regions and their role for the global atmospheric processes (to learn more: https://scar.org/science/research-programmes/agata).

At the time of writing AGATA is organizing its kickoff meeting that will be held from 26–28 March 2025 fully online to optimize and maximize the participation.

The AGATA core members are also working on the promotion of the programme and on the organization of capacity building initiatives to train the next generation of polar scientists. In this framework AGATA, that will have a duration of 8 years (from 2025 to 2032), envisages to have a leading role in the extraordinary activities that will be carried out in preparation and during the next International Polar Year (2032–2033; *https://ipy5.info/*).

This paper will provide an overview of the AGATA first initiatives and opportunities of collaboration and training.

## AS25-0377

# Convection parameterization and model resolution impacts on Joule heating in T-I models

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At polar and auroral latitudes, strong field-aligned currents flow along the Earth's open magnetic field lines. In the ionospheric dynamo region, field-perpendicular Pedersen currents close the circuit. Pedersen currents result in significant Joule heating of the thermosphere-ionosphere (T-I) system which is one of the main geomagnetic energy input mechanisms. High-latitude Joule heating has been shown to cause significant disturbances of the ionospheric electron density. In T-I models, the high-latitude electrodynamics can be parameterized in several different ways, including purely empirical models and data assimilation methods. Model settings like grid resolution and model version can also affect the Joule heating. We evaluate the Joule heating rates calculated from the TIE-GCM and WACCM-X models with those estimated from measurements by the EISCAT incoherent scatter radar in Tromsø, Norway (69.6° N, 19.2° E). We investigate model runs driven with the *Heelis*, *Weimer*, *AMIE,* and *AMGeO* convection patterns. T-I model runs that were coupled to magnetospheric models (*GAMERA*) code are analyzed as well. The grid resolution of the investigated model runs varies from ultra-high 0.25° to regular 1.25° and 2.5° resolutions. We show how the model Joule heating rates are affected by the convection parameterizations, model resolution, and other model settings.

## AS25-0584

# Comparative TEC analysis from low-cost GNSS receiver with GIM model and IRI 2020 model

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The utilization of low-cost GNSS receivers is increasing in the field of ionospheric monitoring in space weather studies[1], [2]. Therefore, in this work, we focus on the analysis of total electron content (TEC) using the low-cost GNSS receivers at Bangkok station, Thailand. Both the low-cost and high-end GNSS receivers (Novatel propak6) are connected with the same geodetic antenna at Engineering building rooftop. The analysis of TEC estimation on quiet days with no ionospheric irregularity in 2024 is made from low-cost receivers then compared with the results of high-end receivers. These results are also compared with the global ionospheric maps (GIM) model and international reference ionosphere (IRI) model[3]. The TEC patterns computed from low-cost and geodetic receivers show good agreement with TEC deviation of less than 5 TECU most of the time. The corresponding $R^2$ and RMSE values are 0.9734 and 3.4583, respectively. However, the TEC from GIM and IRI models are lower than the observed values most of the time during quiet periods.

### Acknowledgment

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## AS25-0803

# Studying the impact of solar flares on ionospheric absorption through multiple stations over Europe during the May 2024 solar storms

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The ionosphere as a highly dynamic interface between Earth's neutral atmosphere and the near-Earth space is subject to a vast spectrum of physical and chemical processes including the phenomena caused by solar storms and solar flares in particular. Solar flares—high-energy outbursts on the surface of the Sun—can have a huge impact on the near-Earth environment: they change the electron density in the different ionospheric layers, resulting in variations in the absorption of electromagnetic (EM) waves. This phenomenon affects the radio communication and the propagation of EM waves through the ionospheric layers.

In order to asses the impact of solar flares on the ionosphere, the received amplitudes of the ionosonde stations can be used to quantify the ionospheric absorption (Buzás et al., 2023). In the present study, we aim to demonstrate the effect of solar flares as mirrored in the absorption data derived from ionosonde measurements from 5 European, mid-latitude stations during the May 2024 solar storms period. The effect of the flares is compared to a quiet diurnal pattern of the absorption at each station whereas other parameters (like the fmin and foE) are used to verify our results.

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## AS25-0820

# Severe Space Weather Events in the North American Low-Latitude Region: Aurora Observations and Ionospheric and Geomagnetic Effects in Mexico

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On 10 May and 10 October 2024, two severe geomagnetic storms produced auroras visible at unusually low latitudes. These storms were the most intense of Solar Cycle 25 so far and marked a milestone for space weather studies in Mexico, enabling comprehensive measurements of their effects. The Mexican Space Weather Service (SCIESMEX) and the National Space Weather Laboratory (LANCE) had been preparing for such events since their inception. LANCE's instrument network recorded solar chromospheric images, solar radio bursts, geomagnetic variations, Schumann resonances, ionospheric disturbances, and energetic particle fluxes. Additionally, Geomagnetically Induced Currents (GICs) were monitored at three strategic substations of the national electrical grid. These observations provided unprecedented insights into the dynamics of severe space weather events in the North American low-latitude region. Citizen science efforts further enriched the study by documenting auroras and regional responses, capturing variations in geomagnetic indices, ionospheric disturbances, cosmic ray fluxes, GICs, and technological impacts.

## AS25-0905

# Advancing Space Weather Research in Heliophysics: Integrating Satellite Missions and Ground-Based Observations for a System-Wide Approach

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Understanding space weather and geospace dynamics requires interdisciplinary, system-wide studies that capture the complex interactions between different regions of the near-Earth space environment. From magnetospheric responses to solar wind drivers to ionospheric and atmospheric reactions to these changes, such investigations rely on a combination of satellite and ground-based observations, as well as advanced modeling techniques that account for coupling across different spatial and temporal scales.

In recent years, community efforts have increasingly focused on fostering collaboration between satellite missions and ground-based instrumentation to integrate datasets strategically, providing a more comprehensive view of geospace as a system of systems. These coordinated efforts hold the potential to significantly advance our understanding of space weather and its impacts. In this talk, we will highlight some of the community's ongoing efforts to enhance collaboration between space missions and ground-based observatories, with a particular focus on NASA's upcoming Geospace Dynamics Constellation (GDC) mission.

To illustrate the need for a cohesive, system-wide approach to space weather, we will examine auroral and subauroral dynamics during both storm and quiet conditions, exploring their connections to the magnetosphere and solar wind. By integrating observations from multiple platforms, this study aims to highlight key mechanisms driving variability and underscore the importance of a unified observational strategy for advancing space weather research.

## AS25-1082

# Effects of ICME and HSS/SIR driven geomagnetic storms on the high-latitude ionosphere-thermosphere

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The main drivers of geomagnetic storms are interplanetary coronal mass ejections (ICMEs) and solar wind high-speed streams (HSSs) with stream interaction regions (SIRs). In this presentation, we show one example of both cases and study their effects on the high-latitude ionosphere-thermosphere (I-T) system. We use a multi-instrument approach with ground-based instruments (e.g., the EISCAT Svalbard and Tromso incoherent scatter radars, GNSS TEC receivers, and magnetometers) as well as satellites (e.g., TIMED, Swarm, and GRACE-FO). The 10–13 May 2024 ICME driven storm was a superstorm (minimum SYM-H -518 nT), while the HSS/SIR drove only a moderate storm on 14–20 March 2016 (minimum SYM-H -69 nT). Both storms caused a depletion in F-region electron density and total electron content (TEC), increase in the ion temperature, and enhanced neutral density at the low-Earth orbit (LEO). While the changes during the May 2024 superstorm were more drastic than during the March 2016 storm, the duration of the changes was longer in the latter one. In the polar cap, 60% of the TEC disappeared during the whole day on 11 May 2024 and the depletion lasted to some extent 3 days, while in March 2016 the depletion in TEC lasted 6 days and was 25–50%. During the superstorm, LEO densities were increased by 300–450%. The processes behind the I-T changes stem from increased Joule heating in the ionosphere, which we estimate for both storms with a new method utilizing data from SuperDARN radars, Ampere project field-aligned currents and SuperMAG magnetometers.

## AS25-1093

# Investigation of Geomagnetic Responses Using Extensive Ground-Based Instrument Arrays

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The interaction between the solar wind and the magnetosphere induces various geospace responses, including ionospheric currents and geomagnetic pulsations. Recent advancements in ground-based observation capabilities have facilitated a more systematic understanding of the solar wind-magnetosphere-ionosphere coupling processes and the transport of energy within the geospace system. Key ground-based facilities contributing to this effort include an Arctic-Antarctic conjugate magnetometer array, a magnetic induction-coil magnetometer array, and low-cost citizen science magnetometers. This study presents observations of geomagnetic pulsations and derived convection patterns during geomagnetic storms and substorms, utilizing the ground-based instrument network with a particular focus on high-latitude regions. Such an extensive ground network offers a valuable opportunity to investigate how geomagnetic responses in these events are linked to external drivers, such as IMF orientation, solar wind flow pressure, solar irradiance, geomagnetic activity, and ionospheric conductivity.

## A09 Analysis of historical magnetic storms for space weather hazards

### AS25-0285

# Comparative analysis of the regional effects of three major geomagnetic storms on Earth's magnetic field response during solar cycle 25

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In this study, we present a comparative analysis of the regional effects of three intense geomagnetic storms observed during Solar Cycle 25. Utilizing data from a global network of geomagnetic observatories positioned across diverse latitudes, we map the geomagnetic field response to these storms. By assessing the spatial distribution of magnetic field variations, we identify the regions most impacted by geomagnetic disturbances.

The comparison of these major storms offers critical insights into the influence of geomagnetic storms on Earth's magnetic field, emphasizing the areas with the most significant disturbances. This research is vital for assessing future risks and developing strategies to mitigate the effects of geomagnetic storms on satellite systems, power grids, and other critical infrastructure, enhancing preparedness in vulnerable regions.

## AS25-0520

# Digitizing the continuous magnetic recordings from London UK for the 1859 Carrington storm

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Dedicated scientific measurements of the strength and direction of the Earth's magnetic field began at Greenwich and Kew observatories in London, United Kingdom, in the middle of the 19th century. Using advanced techniques for the time, collimated light beam was focused onto mirrors mounted on free-swinging magnetized needles which reflected onto photographic paper, allowing continuous analogue magnetograms to be recorded. By good fortune, both observatories were in full operation during the so-called Carrington storm in early September 1859 and its precursor storm in late August 1859. Based on digital images of the magnetograms and information from the observatory yearbooks and scientific papers, it is possible to scale the measurements to International System of Units (SI units) and extract quasi-minute cadence spot values. However, due to the magnitude of the storms, the periods of the greatest magnetic field variation were lost as the traces moved off-page. The digitized magnetic records of the 10-day period from 25 August to 5 September 1859 encompassing the Carrington storm and its lesser recognized precursor on 28 August are shown and their implications for the impact on modern technology in comparison to more recent space weather events are discussed.

## AS25-0850

# Identification of geomagnetic disturbances in near-Earth space from satellite observations during the magnetic storm on March 8–9, 1970

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In this report, we consider historical geomagnetic satellite data obtained during a strong magnetic storm on March 8–9, 1970. In addition to the data of the Soviet satellite Kosmos-321, data from the American satellite OGO-6, which performed geomagnetic measurements at the same time, were used. We analyzed time variations of external magnetic fields recorded in satellite and ground-based observations of the magnetic field. The research also gave impetus to the creation of the improved software implementation of the auroral oval model APM, which enables reconstruction of its position and precipitation intensity in both the past and near real time. The magnetic variations originating in the near-Earth space from various sources were identified. In particular, we revealed the signatures of the storm-time ring current and equatorial and auroral electrojects. The report highlights the enduring value of historical data of magnetic field observations stored in data centers and continuously digitized by their staff.

## AS25-0855

# Extraction of 1-minute values from historical paper magnetograms

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In the past, the variations of the Earth magnetic field were recorded on paper magnetograms. A manual process was needed to produce tables of hourly values, that today are included in digital databases and allow to study the evolution of the magnetic field over several decades.

To enhance the exploitation of these paper data, we developed a software to extract magnetic time series with a higher sampling rate. The resolution of the paper record depends strongly on technology evolutions through the 20$^{th}$ century and the sensitivity on the type of mechanical-optical system used.

For this study we focus on the years 1957 and 1958, the strongest solar maximum of the last century and present data from three observatories managed by French institutes: Chambon-la-forêt (CLF) in France, M'Bour (MBO) in Senegal and Bangui (BNG) in Central Africa, where La Cour magnetometers were deployed. We present data from some of the major magnetic storms.

## AS25-0870

# Historical records of geomagnetic storms from Spanish and Portuguese documents: a review

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The recovery and study of historical geomagnetic storm data represent a fundamental endeavor for advancing research in Space Science, Space Weather, and Space Climate. The Iberian Peninsula offers a unique combination of characteristics that make it an especially valuable region for retrieving and analyzing historical records of geomagnetic storms. First, Iberia possesses an extraordinarily rich documentary heritage. The archives of Spain and Portugal house historical records from many regions across the world that were once part of their global empires. These documents provide invaluable insights into past geomagnetic activity recorded from multiple geographical locations. Second, the region is home to a significant number of geophysical and astronomical observatories with a long-standing tradition of continuous observations, some of which date back centuries. In this contribution, we present a comprehensive review of records of geomagnetic storms preserved in Spanish and Portuguese historical sources. Today, we have recovered numerous historical documents describing auroras observed from Iberia and other parts of the world over the past centuries. However, a complete and systematic catalog of these events has yet to be compiled. In addition, we have access to early instrumental records from geomagnetic and astronomical observatories, which provide critical data for studying and better understanding major geomagnetic storms—such as the remarkable storm of 1903, which occurred during a period of low solar activity.

## AS25-1106

# Temporal and Spatial Evolutions of Extreme Solar-Terrestrial Storm in February 1872

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Extreme solar storms pose significant threats to the technological infrastructure of our modern civilization. This threat makes studies on the temporal and spatial evolutions of such extreme solar storms valuable not only for scientific community but also for broader public audience. In this context, the Carrington event in 1859 has been considered the greatest in the last 2 centuries. However, recent archival investigations have highlighted a rival storm in February 1872 and required scientific attentions. This presentation reviews temporal and spatial evolutions of this extreme storm on multiple aspects on the basis of Hayakawa et al. (2023, ApJ, 959, 23). Contemporaneous sunspot drawings allow us to identify the source active region with a medium-sized but complex sunspot group that crossed the central meridian around 3 February. Contemporaneous magnetograms allow us to locate SSC and estimate the storm magnitude down to < -834 nT in terms of the min Dst estimate. Contemporaneous auroral records allow us to reconstruct the auroral oval extension down to 24.2° in invariant latitude and visibility down to 8.3° in magnetic latitude. This geomagnetic superstorm is more than twice as intense as the May 2024 storm and serves as one of the greatest geomagnetic storms in the last two centuries.

## AS25-1285

# Impact of recent geomagnetic storms on aviation as observed by PECASUS

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Since its operational launch on November 7, 2019, the Pan-European Consortium for Aviation Space weather User Services (PECASUS) has been providing real-time space weather monitoring and issuing ICAO-compliant advisories to the global aviation sector. PECASUS has played a pivotal role in mitigating aviation risks associated with HF communication disruptions, GNSS degradation, and increased radiation exposure at flight altitudes. We will present an overview of selected, significant geomagnetic storms (October and May 2024) as observed via the operations of PECASUS. We provide a brief history of these events (source, evolution) and analyse their effect via the PECASUS advisories. In addition, we will also discuss their impact on ground- and space-based infrastructure, highlighting the importance of space weather monitoring and forecasting. The results showcase how geomagnetic storm analysis can contribute to improving aviation safety. Finally, we will address ongoing and future developments within PECASUS, aiming to further improve the services provided.

## AS25-1314

# The May 2024 Geomagnetic Storm—Challenges in Forecasting

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The May 2024 geomagnetic storm (NOAA Kp = 9) was among the most intense of Solar Cycle 25, driven by multiple Earth-directed CMEs from SIDC Sunspot Group 74 and 75 (NOAA AR 3663 and 3664). This event featured ten X-class flares, complex ICME interactions, and extreme Bz fluctuations (-48 nT), leading to widespread disruptions, including GICs in power grids, HF communication blackouts, severe GNSS scintillation, and satellite anomalies.

For space weather forecasters, this event posed significant real-time analysis and prediction challenges. Rapid assessment of CME propagation, speed, and impact potential relied on tools such as STEREOCat and SWPCCat for initiation parameters, and EUHFORIA and the Drag-Based Model for heliospheric propagation. However, CME-CME interactions made impact predictions highly complex, as successive CMEs altered shock arrival times, enhanced solar wind speeds, and prolonged magnetospheric disturbances, increasing uncertainty in impact assessments.

This presentation will explore the operational challenges faced by space weather forecasters, the differences and limitations of current prediction models, and the need for improved data assimilation and real-time modeling to better anticipate the dynamics of complex geomagnetic storms.

## AS25-1321

# Tracking a Major Geomagnetic Storm in the ESA Space Weather Network: Lessons from April 2023

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Understanding the evolution and impact of major geomagnetic storms is crucial for improving space weather forecasting and mitigating risks to critical infrastructure. In this presentation, we will discuss the April 21–25, 2023 geomagnetic storm, one of the most intense of Solar Cycle 25 (in this case Kp = 8+), as an exemplary case study demonstrating the capabilities of the ESA Space Weather Service Network in monitoring extreme space weather events.

Data from the ESA SWE Service Network Portal enabled a full-chain analysis, from the initial solar eruption, CME tracking, and interplanetary propagation forecasts to the actual geomagnetic storm impacts at Earth. The network's real-time data and post-event analysis showcased both the strengths and limitations of current operational forecasting models, particularly in predicting CME arrival times and geomagnetic storm intensity. This event provided a unique opportunity to assess space weather impacts across multiple domains, including geomagnetically induced currents (GICs) affecting power grids, ionospheric disturbances potentially disrupting GNSS-based navigation, and radiation storms that may increase risks for satellite operations.

Additionally, this event received significant media attention, reflecting the growing awareness of space weather hazards. We will discuss how such high-impact events help refine communication strategies and alert systems, improving coordination among scientific, operational, and public stakeholders.

By leveraging lessons learned from this case, we highlight the key role of historical event post-analysis in refining forecasting capabilities, enhancing early warning systems, and ensuring that the ESA SWE Network continues to support the resilience of space- and ground-based infrastructure against extreme space weather.

## A10 Space weather impact on technology in space and on the ground

### AS25-0058

# GPS Positioning Errors in the Contiguous United States During Severe Geomagnetic Storms

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Space weather poses significant challenges to modern communication and navigation systems. Although mid-latitude scintillation and positioning errors are uncommon, extreme geomagnetic events can severely disrupt these regions. This study investigates key ionospheric structures contributing to Global Positioning System (GPS) position errors over the contiguous United States (U.S.) during two severe geomagnetic storms in 2024. For both storms, strong scintillation and positioning errors were observed near the equatorward boundary of the mid-latitude trough (EBMLT) and substorm precipitation. Additionally, storm-enhanced density (SED) was pronounced and the expansion of the Equatorial Ionization Anomaly (EIA) impacted lower mid-latitude regions, causing outages and preventing Precise Point Positioning (PPP) solutions from achieving accuracy. The spatial distribution of SED varied, with the October storm showing pronounced effects in the eastern U.S., while the May storm predominantly impacted the western U.S. Scintillation at EBMLT during the October storm was relatively weak, resulting in fewer PPP errors compared to the May storm. Similarly, the EIA was also weaker during the October storm, which contributed to a lower magnitude of PPP error compared to its May counterpart.

## AS25-0118

# Modelling geomagnetically induced currents in a gas pipeline in Spain

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While geomagnetically induced currents (GICs) have been extensively studied in Spain over the last decade, the country has extensive gas and oil pipeline networks, whose vulnerability to GIC hazards has not yet been assessed. A buried pipeline coated with a protecting electrical insulator has a voltage difference between the surrounding soil and the steel of the pipeline. This voltage difference varies along the conductor due to the ambient geoelectric field and the current flow along the pipe walls, the latter being modulated by the steel resistivity. In turn, this voltage difference causes a current to flow between the pipe and the soil that is modulated by coating conductivity. These two ideas are the basis of the distributed-source transmission line (DSTL) theory as the methodology for modelling magnetic induction in pipelines, which we have tested for the first time in a gas pipeline running roughly north-south in western Spain. To solve the model, the diameter and conductivity of both the pipeline and its coating were needed for each section, along with the topology of the pipeline and its branches and the positions of the insulating flanges. As an output of the model, the Pipe to Soil Potential (PSP) and the current flow (GIC) in the pipeline are obtained and compared with actual measurements during several geomagnetic storms.

## AS25-0192

# Space Weather Models for LEO Satellites: Progress and Future Plans

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With the rapid increase in the number of satellites in Low Earth Orbit (LEO), tailored space weather forecasting has become essential for satellite operations. This presentation summarizes ongoing research aimed at developing a space weather model for LEO satellites. The project focuses on key issues, including spacecraft charging phenomena, high-energy particle exposure, orbital decay due to atmospheric drag, and collision risks among satellite constellations. Initial efforts have successfully integrated satellite charging simulations using the Spacecraft Plasma Interaction System (SPIS), evaluated high-energy particle distribution models (AP8, VERB), and improved orbit prediction accuracy with modified atmospheric models, such as SGP4 combined with NRLMSISE-00 and JB2008. Furthermore, collision risk assessment indices, such as the Collision Rate Percentage Increase (CRI), have been adopted to quantitatively evaluate risks within large constellations. This ongoing work aims to enhance the accuracy and timeliness of space weather forecasting, ultimately supporting safer and more efficient satellite operations in the rapidly evolving LEO environment.

## AS25-0402

# Cumulative and extreme storm risks to the New Zealand gas pipeline network

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Space weather presents a risk to gas pipelines through both cumulative effects that can lead to corrosion and/or disbonding of the pipeline coating from the pipe, and from extreme events which may disrupt or damage the cathodic protection (CP) mechanism. We worked together with a gas transmission operator in New Zealand to develop and validate two techniques – direct modelling of the pipeline network, and transfer function relationships between observed potentials on the CP system and magnetic field variations – to investigate and attempt to quantify these risks. We have used these two techniques to predict both the risk during a reasonable worst case scenario extreme solar storm, and the cumulative risk over several years from less severe storms. The annual risks of corrosion and disbonding depend largely on the total amount of time in a year that pipe-to-soil potentials (PSPs) are either positive, or excessively negative, respectively. Locations showing the longest lengths of time where these conditions exist are largely at the northern, southern and eastern extremities of the network. During extreme storms dangerously large pipe to soil potentials on the pipe which may effect CP rectifiers depend on the distribution of earthing sites, and the safe operating range is exceeded for a significant period of the storm at most locations.

## AS25-0404

# Geomagnetically Induced Current research in New Zealand: the Solar Tsunamis research programme

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Large geomagnetic disturbances are a known space weather hazard to power transmission networks due to the effects of Geomagnetically Induced Currents (GICs). Extreme space weather events occurring with 100 year return periods may produce significant damage and disruption to electricity networks and supply.

New Zealand provides a high-quality "laboratory" for GIC research. While being at mid-latitudes magnetically, measurements exist for GIC, harmonic distortion, and reactive power changes. More importantly the power network operator is willing to collaborate with local space weather researchers to investigate the space weather hazard. This collaboration has extended to providing observations and the detailed network parameters needed for validated modelling. The "Solar Tsunamis" research programme is 5-year research project aimed at understanding the risks posed by space weather events in New Zealand energy networks, principally electrical and natural gas pipelines. A significant goal of our research is to assist in the development of routes by which the GIC risk can be mitigated in the New Zealand electrical network.

The programme is now in its last year, and has had a number of successes. In this presentation I will discuss the questions posed by our industry partners, the primary work packages developed to address those questions, and our new results. While our research is very New Zealand-focused, New Zealand spans an geomagnetic latitude range spanning much of Europe (Gothenburg to Budapest) and North America (Vancouver to San Francisco).

This presentation is part of the New Zealand Solar Tsunamis programme, MBIE Endeavour Fund Research Programme contract UOOX2002.

## AS25-0407

# GIC-driven reactive power responses of a single phase unit transformer during multiple geomagnetic disturbances

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Geomagnetic storms represent a space weather hazard to power transmission networks due to the effects of induced geo-electric fields within the conducting surface of the Earth. These drive electric currents in power transmission lines which can flow to ground through the neutral-ground connections of transformers. Geomagnetically induced currents (GIC) can negatively impact the operation of high voltage transformers through asymmetric half-cycle transformer core saturation. However, there are few measurements defining the response of susceptible transformers, and the majority of insight has previously been gained from modelling efforts.

In this presentation GIC measurements and reactive power responses (Q) from the single phase bank transformer, T4, operating in the Halfway Bush substation, Dunedin, New Zealand have been analyzed over the period 2013–2017. During seven high GIC periods linear enhancements of reactive power consumption (Qcon, MVAr) were seen when GIC levels increased, even from very low levels of GIC. This is consistent with transformer core saturation where there is little tolerance or 'headroom' to GIC in the design of the transformer.

Reactive power measurements show high variability and the removal of the non-GIC variability is difficult. This introduces uncertainty into the identification of GIC-driven responses. In this analysis we consider two techniques to isolate GIC-induced reactive power responses. We find that transformer T4 exhibited a reactive power response of 0.04 -0.08 MVAr/A depending on the technique applied. The results are broadly similar to our recent findings characterising 3 phase transformer responses to GIC, although with less 'headroom' in the design.

## AS25-0415

# Implementing GIC mitigation during the May 2024 'Gannon' G5 storm: Research informed response by the New Zealand Power Network

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In early May 2024 approximately six Coronal Mass Ejections were launched towards the Earth in short succession. This triggered the G5 "Gannon" geomagnetic storm producing auroral displays visible globally including at lower latitudes than previous geomagnetic disturbances this century. Magnetic field variations measured in terms of dH/dt at multiple sites in New Zealand surpassed those observed since 1989, before digital records began.

In 2022, following many years of industry-research collaboration as part of New Zealand's Solar Tsunamis programme, an updated and enhanced "All of New Zealand" Geomagnetically Induced Current (GIC) mitigation strategy was developed. This strategy involves targeted line disconnections to reconfigure the network to reduce GIC magnitudes and durations at the most at risk transformers, while still maintaining the continuous supply of power. Following training of control room staff, this strategy was declared operational in mid-2023.

When disturbance levels reached the G5 threshold during the Gannon storm Transpower control room staff followed the planned procedure and implemented the mitigation strategy for the first time. There was no impact to New Zealand's electrical supply from this storm. GIC was measured at more than 70 transformers throughout the New Zealand power grid. Peak GICs observed after the mitigation strategy was in place reached ~113 A at a transformer in the city of Dunedin. Without mitigation, modelling shows that a peak GIC of ~200 A through the neutral would have occurred, exacerbated by the tripping of a transformer at a neighbouring substation.

## AS25-0442

# Comparison Between Low-Cost and Geodetic GNSS receivers on ROTI Analysis at a Low-Latitude Station in Thailand

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With the advancement of Global Navigation Satellite System (GNSS) technology, low-cost GNSS receivers with compactness, multi-constellation, and multi frequency chipsets, are highly in demand in recent years[1–3]. These receivers offer new opportunities for monitoring the upper atmosphere using GNSS signals[4–5]. However, low-cost receiver utilization for ionospheric irregularity around Thailand has not yet been explored. In this work, therefore, we analyze the ionospheric parameters on days with ionospheric irregularities. For this, the rate of total electron content index (ROTI) values with 5-min window size computed from the low-cost GNSS receivers are analyzed from the logged 1s GNSS datasets in 2024. In the experimental setup, on our campus in Bangkok, Thailand, both the low-cost receivers and the geodetic GNSS receivers are co-located at the same facility and connected to the same geodetic antenna for comparison purpose. Additionally, the calibration of TEC gap bounds is made to find suitable gap bounds for low-cost GNSS receivers.

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## AS25-0500

# The extreme GICs occurrence during 11 years of observations in the North-West of Russia

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The work analyzes the extreme values of geomagnetically induced currents (GICs) over quasi solar cycle (2012–2022) in power lines in the northern-west Russia (Kola Peninsula and Karelia). The auroral station Vykhodnoy (VKH) and the subauroral station Kondopoga (KND) are considered. It was selected 92 extreme events (GIC >20 A) for the VKH station and 31 extreme events (GIC >5 A) for the KND station.

For the VKH station during CME magnetic storms ~51.1% of extreme GICs were observed, 36.9% occurred during CIR magnetic storms, 3.3% events are caused by SC and 8.7% events occurred without magnetic storms. So CIR storms and even intervals without storm should be also taken into account during forecast of the space weather influence on power lines.

For the subauroral KND station during CME magnetic storms ~80.6% events were observed, 12.9% events occurred during CIR magnetic storms, ~6.5% took place without a magnetic storm. Thus, with decreasing geomagnetic latitude, CME storms cause a greater number of extreme GICs.

Most extreme bursts of GICs were caused by substorms and were observed in both the pre-midnight and post-midnight sectors of the MLT. Distributions of extreme GICs were obtained depending on the parameters of the interplanetary medium (V, Bz, V·Bs, ε), geomagnetic activity indices (SYM-H, AE, IE), and dB/dt variations. A positive trend is observed for the |GIC|-SYMH and |GIC|-|dB/dt| dependencies.

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## AS25-0680

# Minute-level LSTM forecasting of ionospheric amplitude scintillation in Thailand

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Ionospheric irregularities significantly impact satellite-based applications, particularly the Global Navigation Satellite System (GNSS), by inducing scintillation in radio wave propagation [1]. Among various space weather phenomena, ionospheric scintillation is a critical issue characterized by rapid fluctuations in the amplitude and phase of transionospheric satellite signals. Amplitude scintillation, which primarily occurs in low-latitude regions including Thailand, is known as one of dominant factors affecting GNSS performances. To mitigate its adverse effects, timely and accurate forecasting of scintillation occurrences is necessary.

In this work, we propose a long short-term memory (LSTM) model for the minute-level forecasting of the amplitude scintillation in Thailand. To capture short-term severe scintillation events, simple upsampling-based feature preprocessing with the upsampling rate of 5 minutes is presented for further enhancing the model performance. Utilizing a dataset collected during the solar maximum period in 2024, characterized by a high occurrence of scintillation, our fine-tuned LSTM model with feature preprocessing significantly outperforms standard LSTM and other machine learning models with the $R^2$ value increasing from 0.7248 to 0.8764, implying an approximately 21% enhancement. Furthermore, compared with existing studies [2], the proposed LSTM model establishes a new benchmark for amplitude scintillation prediction by achieving superior accuracy in 1-day-ahead forecasting.

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## AS25-0723

# Revisiting GIC predictions in the UK power grid using a new geoelectric field model based on long-period magnetotelluric data

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Geomagnetically induced currents in high voltage power lines are a recognised geohazard in many high and mid-latitude countries. For their accurate characterisation and mitigation strategies, sophisticated models of the inducing geomagnetic field, the ground response due to the geology and the power network need to come together. In the UK, the GIC hazard has been studied for decades with ever improving models of geomagnetic field, conductivity distribution in the crust and mantle, and the topology of the power network. However, the limiting factor was our knowledge of the ground electric field response. Between 2021 and 2024 we collected 53 new long-period magnetotelluric sites across Britain and added in data from a further 17 locations from legacy sources. We focus on the effects of the recently improved geoelectric model using the newly collected magnetotelluric data. With the new model we revisit GIC simulations in the UK power grid for the strongest geomagnetic storms of the past decades, identifying previously unknown areas with increased GIC hazard including central England and northern Scotland.

## AS25-0737

# A Transformer-Based Forecasting Model for GNSS-VTEC and its Application Study Over Nigeria

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This paper introduces a novel approach using the channel-independent Patch Time Series Transformer (PatchTST) for GPS-VTEC forecasting in Nigeria. This is the first application of the PatchTST framework for ionospheric prediction. The GPS-VTEC dataset is constructed from ionospheric monitoring stations in Nigeria, incorporating key influencing factors such as seasonal changes, diurnal patterns, magnetic activity, and solar activity. The model is trained on data from 2012–2021 and evaluated on 2022 data, a period of high solar activity. We compare the performance of PatchTST with Multilayer Perceptron (MLP), Long Short-Term Memory (LSTM), BiGRU, and CNN-BiGRU models using root mean squared error (RMSE), mean absolute percentage error (MAPE), and correlation coefficient (R). PatchTST outperforms other models with an RMSE of 4.731 TECU, a MAPE of 2.351%, and an R-value of 0.986 in both short-term (1-day) and mid-term forecasting. The hybrid CNN-BiGRU model also shows strong predictive performance, achieving an RMSE of 3.046 TECU and an R-value of 0.896, effectively capturing diurnal variations. Uncertainty analysis highlights PatchTST's superior adaptability, with a 62.9% improvement in mean error (ME) and a 40.5% improvement in standard mean error (STDE) compared to benchmark models. Additionally, PatchTST surpasses empirical models like IRI-2016 and NeQuick-2 in capturing seasonal variations. This work demonstrates the effectiveness of PatchTST in improving GPS-VTEC forecasting accuracy and its robustness under uncertain conditions, marking a significant advancement in ionospheric prediction

## AS25-0788

# Modelling pipe-to-Soil potentials in Great Britain during extreme events

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Large geomagnetic field variations during geomagnetic storms induce telluric currents in pipelines. These currents can lead to variations in the pipe-to-soil potentials (PSPs) which can interfere with corrosion-prevention measures and may enhance corrosion, or cause disbonding, leading to localised damage and a reduced lifetime of the pipeline. Modelling PSP fluctuations is useful for developing mitigation measures and important for understanding possible safety implications during pipeline testing and maintenance as well as understanding where the PSPs may be largest.

BGS have been running a model of the British high-pressure gas pipeline network, which provides an estimate of PSPs in near-real-time, for several years. Here we present recent efforts to improve the model, building on expertise developed through research undertaken in New Zealand, where there are more observations of PSPs available. We also include improvements to the underlying electric field model and investigate the impact of extreme events.

## AS25-0913

# Geomagnetically induced currents in the North Island of Aotearoa, New Zealand

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Magnetotelluric (MT) data measured over the past 25 years, including a recent survey of 53 long period sites in the northernmost part of the North Island, have been used to assess the risk posed by geomagnetically induced currents (GIC) to the electrical transmission network in the North Island of Aotearoa, New Zealand. MT transfer functions have been combined with local magnetic observatory data to compute electric fields across the entire North Island for several recent geomagnetic storms. Superposition of the calculated electric fields on the topology of the transmission network reveals that maximum GIC of nearly 30 A occur in transformers located near Auckland. Calculations of GIC in the actual transmission lines are used to explore why GICs occur preferentially in these transformers.

## AS25-0968

# How spatial resolution of conductivity models affects GIC estimation: case study in a geological complex region

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This study examines the influence of the underground electrical conductivity model spatial resolution on Geomagnetically Induced Currents (GIC) in a power grid within southern Portugal's geologically complex region. The accuracy of GIC estimations depends on reliable subsurface conductivity models, as they govern the geoelectric field response to geomagnetic disturbances. We compare GIC simulations using two conductivity models, one based on a sparser and the other on denser magnetotelluric sounding distributions. To compare corresponding simulated GIC time series, we introduce the Correlation Regression Coefficient (CRC), a statistical measure that considers both deviations to linearity and rescaling of different time series. Higher CRC values indicate more significant differences between the two time series. Other parameters, such as GIC standard deviation and peak values, are also affected, with relative variations exceeding 100% in some cases.

Additionally, we evaluate the effectiveness of local and regional proxy methods in capturing GIC variations. Results show that a regional proxy, which accounts for the influence of conductivity contrasts in regions crossed by transmission lines converging to a certain substation, represents more closely the GIC behaviour than a purely local proxy. These findings emphasize the need for high-resolution conductivity models to improve GIC impact assessments, particularly in regions with complex geology where conductivity variations can significantly influence the electric field.

## AS25-1348

# A new space weather effect on wintertime electricity consumption and wind power production in Finland and other European countries

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It is known that electricity consumption in many cold Northern countries depends greatly on prevailing outdoor temperatures especially during the winter season because energy is needed for heating. On the other hand, production of electricity by wind power is also heavily dependent on weather conditions.

Recent research has demonstrated that solar wind driven energetic particle precipitation from space into the polar atmosphere can influence the stratospheric polar vortex and tropospheric weather patterns during winter via catalytic ozone loss it induces in the stratosphere. These changes are significant, e.g., in Europe, especially in Northern Europe like Finland.

We demonstrate here, for the first time, that geomagnetic activity, as a proxy of energetic particle precipitation, significantly influences the variability of Finland's average wintertime electricity consumption as well as production of wind power in many European countries including Finland. However, we highlight that these particle precipitation related influences are only seen when the prevailing equatorial stratospheric winds, so called QBO winds, are easterly.

Our results demonstrate a previously unrecognized societal influence of space weather, and imply that long-term energy consumption and production forecasts could potentially be improved by considering long-term space weather predictions.

## AS25-1403

# Advancing the Lead Time of Space Weather Forecasting: Current Knowledge and Prospects for Solar Cycle 26

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High-accuracy space weather forecasts for geomagnetic conditions are released with about one hour lead time based on solar wind and interplanetary magnetic field (IMF) measurements from the Sun-Earth L1 point. Advancing the lead time to 6, 24, or 48 hours is one of the priorities for space weather as outlined by end users, researchers, and the 2024 US Heliophysics decadal survey. However, the required accuracy of such forecasts is rarely discussed. Here, we review what advances are needed to improve the lead time of forecasts. 48-hour lead time implies predicting fast coronal mass ejections (CMEs) before they occur, which requires significant improvement in our physical understanding of the solar interior, active region evolution and CME formation and evolution. 24-hour lead time may be achievable with a multi-billion euro investment in our space weather observing and modeling capabilities, combining multi-point remote and in-situ measurements from off the Sun-Earth line and off-the-ecliptic, as well as data-assimilation in real-time large-scale modeling. 6-hour lead time may be achieved with a much smaller (~100–200 million euros) investment by focusing on in-situ measurements sunwards of L1 (sub-L1 monitors). Recent measurements by STEREO-A and Solar Orbiter have shown the promises of such an approach but also revealed how our current knowledge gaps about CMEs and shocks limits our ability to design such an operational mission at this time. A space weather research pathfinder or hybrid science and operational mission would be required to enable such advancement in our forecasting capabilities by the maximum of solar cycle 26.

## AS25-1410

# Ground electric field, atmospheric weather and electric grid variations in Northeast Greece influenced by space weather in March 2012

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The present study examines the influence of space weather in Thrace, Northeast Greece, after two strong solar flares on March 7, 2012 (00:24 UT and 01:14 UT). The solar activity induced a superstorm (with minima in the Dst index on 7, 9, 12 and 15 March), while extreme weather events occurred all over the globe. In particular, we note the historic March 2012 heat wave in the Northeast United States. Our data analysis suggests that: (i) Between 3–31 March, the temperature in Thrace (Alexandoupoli) and the ACE/EPAM solar high energy (1.88–4.70 MeV) proton flux were strongly anticorelated ($r = -0.75$, $p = 0.5$). (ii) at the beginning of the two above mentioned periods large atmospheric electric fields were recorded, with values ranging between ~−2000 V/m and ~1800 V/m on 8 March. Finally, we analyzed data from the electric power network in Thrace (~41◦N).˝We found that (a) sudden voltage changes (SVCs) within 1 sec (SVC > 500 V than the existing average voltage value in the last 5 s) in the high (150 kV) voltage electric power network in Thrace were recorded on magnetically disturbed days, i.e., 7 and 10 March 2012 and (b) many more sudden voltage disturbances occurred in the electric grid in Thrace on 10 March than on 9 March indicating a preference for the recovery phase of the storm. The novel finding of the geomagnetic effects on the electric power grid in Thrace may open a new window into space weather applications research.

## AS25-1416

# Uncertainty quantification and machine learning in space weather forecasts

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The solar wind (SW) is a key driver of space weather (SWx) at Earth and throughout the solar system. The structuring of the SW into fast and slow streams is the source of recurrent geomagnetic activity. The largest geomagnetic storms are caused by solar coronal disturbances called coronal mass ejections (CMEs) that propagate through and interact with the SW. Data-driven modeling of stream interactions in the background SW and of CMEs propagating through it, is a necessary part of SWx forecasting. It should be based on time-dependent connections between eruptive events, magnetic phenomena on the Sun, and SW structures in the solar atmosphere and inner heliosphere (IHS). Substantial success has been achieved in numerical modeling of the IHS, but predictive capabilities are far from satisfactory. While there are likely several reasons for this, two difficulties are quite clear. The first issue is that numerical approaches used to attack SWx problems may not adequately capture important features of discontinuity formation, interaction, and propagation from the Sun to Earth. The second is that global modeling of the time-dependent IHS requires boundary conditions (b.c.'s) that incorporate remote and *in situ* observations of the Sun. The b.c.'s being incomplete, predictive capabilities of numerical simulations become uncertain. They require ensemble modeling and uncertainty quantification. Our analysis of the ambient SW and CMEs propagating through it show that uncertainties are typically not acceptable, even for determining CME arrival time at Earth. We propose machine learning (ML) techniques that make it possible to improve SWx forecasts.

## A11 AC - DC Global Circuit for Atmospheric Remote Sensing

### AS25-0096

# Imaging the low-frequency radio sky with ALFA (African Low-Frequency Array)

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The first glimpses on the low-frequency radio sky above the Karoo desert in South Africa exhibit new signals of unknown origin alongside intermittent pulses from lighting leaders and cloud-to-ground strokes in addition to continuous radio transmissions. Lightning detections are compared to reports of lightning occurrences by the new Lightning Imager on board the Meteosat Third Generation geostationary satellite (MTG-LI) during January 2025. The African Low-Frequency Array (ALFA) records radio waves from ~1–400 kHz with an interferometric array of three receivers deployed in a triangular network spread over a square kilometre. The arrival azimuths and elevation angles of the Poynting vectors from radio sources are determinedby coherency spectra that are integrated over various temporal scales to investigate the nature of persistent continuum, or background, radiation. The persistence is identified from significant deviations of the coherency during the temporal integration when compared to entirely random processes. The absence of coherency in some parts of the spectrum is attributed to local interference. Some of the detected sources in the sky exhibit significant coherencies as part the continuum radiation without a currently known origin which is discussed in more detail.

## AS25-0159

# The Poynting flux of transient luminous events

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We present the first Poynting flux observations of lightning associated with transient luminous events (TLE) observed during the summer over South Africa. In addition to optical cameras, the vertical electric field (<400 kHz) and horizontal magnetic field (<60 kHz) perturbations were observed from the ground. For 28 monostatic observations in 2019, we show that the Poynting flux magnitude dominates over the local ionospheric Joule heating, which dominates over the TLE photon flux. In 2023, the radio wave observations were extended to include 3 sites with ~2 km equilateral spacing, two of which had 2-axis horizontal electric field observations and one of which had 3-axis electric and magnetic field observations. For 9 events, we show that the Poynting flux direction is broadly consistent with the TLE parent lightning strike. The association between the Poynting flux and TLE photon flux directions is presented.

## AS25-0218

# Is the global lightning occurrence affected by solar activity?

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Cross-correlation between annual lightning/thunder counts and solar activity was examined globally for the period 2009–2022 using data from World Wide Lightning Location Network. Such analysis, using the global lightning data, has not been done before. Regions of significant cross-correlation or anticorrelation ($p < 0.05$) between annual lightning/thunder counts and solar activity or selected parameters of solar wind are presented. A potential influence of El Niño–Southern Oscillation is also discussed.

Our results do not support previously published hypotheses indicating that cosmic ray intensity (which is anticorrelated with solar activity) should be in phase with the global lightning frequency. We do not exclude that cosmic rays help ignite lightning in developed thunderclouds and that energetic particles precipitating from the magnetosphere affect the frequency of lightning in the region of the South Atlantic Anomaly of the geomagnetic field.

## AS25-0244

# Lightning superbolts used to follow ship-tracks in Eastern Mediterranean winter thunderstorms

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The effects of ship exhaust on ocean cloudiness have been studied intensively in recent years, following the discovery of prolonged ship tracks in oceanic regions where maritime transportation is heavy, leading to large-scale changes in albedo and reduced precipitation, and also in lightning activity (Thornton et al., 2017). We study the effects of ship-emitted aerosols on thunderstorms in one of the busiest shipping routes in the world: the Mediterranean Sea between the Suez Canal and the Gibraltar Straights. This region hosts hundreds of ships daily, and space observations show considerable enhancement of the Aerosol Optical Depth (AOD) and NOx concentrations there, some from land sources and others directly related to ships. We analyzed ENTLN data of winter thunderstorms occurring in the eastern Mediterranean from December 2017–February 2022 (5 winter seasons). Results show a marked increase in lightning activity over the main east-west shipping lanes, where a conspicuously larger fraction of superbolts (Ip > 200 kA) is observed. However, detailed seasonal analysis shows interesting changes following the new regulation imposed by the IMO reducing sulfur emissions from 3.5% to 0.5% since January 2020. This led to a pronounced decrease in lightning flash density above shipping lanes from February 2020, and the enhancement signal is almost gone. Apparently, the removal of ship emissions changed cloud microphysics and diminished the effectiveness of charge separation processes, leading to reduced lightning activity above shipping lanes in the Eastern Mediterranean Sea.

## AS25-0327

# Temporal dynamics in the intercomparison of thunder hours and lightning-clusters

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A thunder hour is defined as an hour during which thunder is heard within a ~15 km radius (DiGangi, BAMS, 2022). Alternatively, thunderstorms can be estimated using lightning clusters, where each event is identified as a set of contiguous lightning grid boxes with more than one stroke, either laterally or diagonally (Ccopa et al., JASTP, 2021). In this work, we conduct an intercomparison between Thunder Hours and Thunderstorms across multiple timescales from 2014 to 2023. Our results show a strong correspondence between both parameters, with a Pearson correlation coefficient exceeding 0.9 in their average daily variations. Both indicators exhibit similar seasonal cycles, with maxima during the Northern Hemisphere summer (June–July–August) and minima during the Southern Hemisphere summer (December–January–February). Spectral analysis reveals significant periodicities at 0.5-, 1-, and ~360-day scales for both datasets. Notably, a 45-day periodicity appears exclusively in the Thunderstorm data, potentially linked to the Madden-Julian Oscillation (MJO). This hypothesis is further examined through a case study of the strong MJO event observed between January and March 2018. Finally, anomaly analysis for 2023 (baseline: 2018–2022) confirms coherent signals between both indicators, highlighting increased electrical activity over the eastern tropical Pacific and the northern Maritime Continent, and decreased activity in southern parts of the Maritime Continent.

## AS25-0392

# A decade of Schumann resonance monitoring in Mexico: insights into the Global Electric Circuit

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Since 2012, the Mexican Schumann resonance station located at 19.8° N, 101.7° W, has continuously monitored and recorded Extremely Low Frequency (ELF) electromagnetic signals in the 0–40 Hz band. We present time series and spectral analyses of data collected over the past decade using two inductive antennas and one capacitive antenna. Since Schumann resonances are generated by global thunderstorm activity, we identified the diurnal amplitude variations of the first three modes and their association with the three major thunderstorm centers: the Americas, Africa, and the Maritime Continent. These observations provide insight into the role of global thunderstorm activity and its possible implications for atmospheric coupling processes in the AC global circuit, contributing to the remote sensing network of the Earth's atmospheric electrical environment from central Mexico. Additionally, we analyze anomalies linked to other geophysical phenomena related to ionospheric disturbances.

## AS25-0396

# Effect of Atmospheric Gravity Waves generated by Thunderstorms in the Ionosphere and Schumann Resonance Modes

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Atmospheric Gravity Waves (AGWs) are essential in ionospheric dynamics, acting as a coupling mechanism between the troposphere and the ionosphere. Among the tropospheric sources of AGWs, thunderstorms can induce variations in ionospheric plasma, which are observable in the distribution of the Total Electron Content (TEC), defined as the electron density integrated along a vertical column of the ionosphere.

In a previous study, we analyzed the ionospheric variations induced by thunderstorms (00:00–08:00 UTC) on November 10, 2018, in Argentina, comparing them to a non-storm day. TEC data were supplied by the Argentine Continuous Satellite Monitoring Network (RAMSAC by its acronym in Spanish) and Atmospheric Electrical Activity (AEA) data were provided by the Earth Networks Total Lightning Network (ENTLN). AGWs with peak-to-peak amplitudes of up to 1.35 TECU were detected, being 2.91 times larger on stormy days. The largest amplitudes coincided with periods of intense AEA, suggesting a strong correlation between lightning activity and AGW intensity.

Schumann Resonance (SR), a global electromagnetic phenomenon within the Earth-Ionosphere waveguide, is excited by lightning. Its resonance modes (≈8 Hz, 14 Hz, 20 Hz, 26 Hz) reflect ionospheric changes associated with solar activity, geomagnetic storms, and tropospheric phenomena. Domingo et al. (2022) found a correlation (>0.52) between the first SR mode (00:00–07:00 UTC) and TEC. This study extends our previous work (Villagrán Asiares et al. (2023)), analyzing the influence of AGWs on SR modes, thus contributing to our understanding of troposphere-ionosphere coupling and the global electrical circuit.

## AS25-0417

# From local to planetary scale: atmospheric electric field in Buenos Aires

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The potential gradient (PG) is a key variable in the study of atmospheric electricity since it allows the detection of both local phenomena and thunderstorms on a global scale under Fair Weather (FW) conditions. This work analyses the variations of PG (FW) as a function of the influence of traffic flow in Buenos Aires. Using data on PG, nitrogen dioxide ($NO_2$), vehicle flow and atmospheric optical depth (AOD), significant weekly variations were identified, with a mean decrease in PG(FW), vehicle flow and $NO_2$ concentrations during weekends, especially on Sundays. In contrast, no significant correlations were found between PG and AOD, nor were weekly changes associated with AOD, possibly because AOD measures aerosols throughout the atmospheric column. Analysis using the Lomb-Scargle periodogram showed a predominance of the daily cycle and the existence of a significant seven-day cycle probably associated with human activity. The days with less influence of traffic (Sundays) showed mean daily variations of PG (FW) with the same quarterly pattern as the global circuit, demonstrating the persistence of the global signal in Buenos Aires. During the 2020 COVID-19 lockdown, analyses reflected results consistent with the above weekly patterns: PG and $NO_2$ decreased along with vehicular traffic, strengthening the relationship between these variables. This work shows how anthropogenic activities, especially vehicular traffic, affect PG (FW) in Buenos Aires, while the global signal remains dominant despite local influences.

## AS25-0481

# Studying electromagnetic seasons using an almost 22 years-long time series of Schumann resonance frequencies

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The seasons are yearly recurring time periods of the year where the days exhibit broadly similar characteristics (e.g., the mean temperature for meteorological seasons). Also being linked to the latitude of the Sun, characteristic variations of atmospheric electricity parameters can be used to define electromagnetic (EM) seasons. It is well documented that the daily frequency pattern (DFP) of the Schumann resonance (SR) modes provide a solid basis for this approach.

In this study, we used the time series of the 1st and 2nd mode DFP correlations from the years 1994–2016 to revisit the methods for determining the length of the EM seasons, the changing of their lengths over the covered time period, and the consistency of the results obtained from the two considered SR modes. We analyzed the vertical electric component of the atmospheric EM field from NCK (47.63° N, 16.42° E), a midlatitude SR monitoring station in Europe.

It was found that the position and the length of the EM seasons within the year depend on the applied analysis method and (slightly) on the SR mode selected for the evaluation, too. We suggest a method that can be applied to SR data recorded at a station of any latitude. Nevertheless, the preferred location of a SR station is discussed in this aspect. The results clearly show that the January-like main EM season is the longest one. The consistent (albeit insignificant) trend in its length suggests that this season has been lengthening in the past 2–3 decades.

## AS25-0586

# Drivers of Superbolt occurrence in the Central Andes (2010–2024)

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This study analyzes the factors contributing to the high density of Superbolts—extremely high-energy lightning discharges greater than 1 MJ— over land in the central Andes region, from 10° S to 35° S latitude and from 60° W to 80° W longitude, covering northern Chile and Argentina, Bolivia, and parts of Peru and Brazil. Based on previous studies that identified Superbolts in this area and using 15 years of data from the World Wide Lightning Location Network (WWLLN) (2010–2024), we examine their spatial and temporal distribution. Preliminary results identify approximately 1000 Superbolts, showing a high frequency between December and March, with 2014 and 2015 as the most active years. Particularly, we find that the sunspot number varies similarly to the upper envelope of the Superbolt distribution, both peaking in 2014, suggesting that solar factors might influence the occurrence of these extreme lightning events. We hypothesize that the South American Low-Level Jet (SALLJ) plays a significant role in shaping the conditions conducive to Superbolt-producing thunderstorms. The SALLJ, which transports moisture from the Amazon to the subtropics, influences deep convection and precipitation, especially over the La Plata Basin (LPB). To explore these connections, we analyze ERA5 reanalysis data, using 75$^{th}$ percentile thresholds for wind speed and wind shear, computed for 1984–2024, to identify SALLJ events. Finally, we consider the role of topography, knowing that Superbolts occur over the Andes. This study seeks to clarify whether these atmospheric drivers, in combination with solar activity and topography, are responsible for the enhanced occurrence of Superbolts in this specific region.

## AS25-0700

# Analytical modelling of Earth-ionosphere cavity resonances produced by lightning discharges with a continuing current

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In lightning research, there is a growing interest in measuring the extremely low frequency (ELF, 3 Hz–3 kHz) electromagnetic (EM) radiation of lightning, as this frequency band can be used to infer different characteristics of lightning discharges that are currently not available from state-of-the-art lightning detection networks. One of these characteristics is the presence of a continuing current (CC), which can last for hundreds of milliseconds and therefore poses an increased risk of physical lightning damage. In this contribution, we investigate the modelling possibilities of the Earth-ionosphere cavity resonances excited by lightning with a CC using a modified version of a well-known analytical model describing Schumann resonances (SRs) and a full FDTD model. Since analytical models are much faster and require significantly less memory than numerical models, they are widely used to interpret ELF measurements. However, analytical models need to be validated as they rely on considerable simplifications. Here we demonstrate that the theoretical ELF spectra provided by our analytical model show good agreement with the FDTD calculations for both the impulse-like (imitating SRs) and exponentially decaying (imitating the presence of a CC) excitation sources. Our results confirm that the analytical model is well suited to interpret ELF measurements for the purposes of studying global lightning activity or individual lightning discharges.

## AS25-0714

# Investigating potential gradient anomalies: insights from a short measurement campaign at a suburban site in northeastern Germany

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We discuss several practical challenges with calibrating and interpreting multi-year in-situ potential gradient (PG) measurements with a Campbell CS110 electric field mill performed at a suburban site in Magdeburg (Northeastern Germany). Notably, PG measurements from Magdeburg exhibit unusually small mean values and daily variability compared to other sites. While expected fair weather PG values should be of the order of 100 V/m, the local instrument recorded a median value of only 13.5 V/m during four years of almost continuous operation so far. The diurnal variation shows a single peak, with values ranging from 5 to 20 V/m.

To address and correct for potential instrument and site-specific effects, a parallel measurement campaign was conducted in the summer/fall of 2024 using an identical reference instrument placed at different places less than about 200 meters from the original field mill. Based on the obtained parallel measurements, we identify different types of discrepancies between co-located electric field measurements and clarify their underlying causes. While environmental or location-related issues were not found as causes, the observations suggest other (instrument-specific) factors requiring further exploration. The daytime reference measurements provided a statistical correction for the original observations that is employed for correcting ongoing measurements. The resulting time series of local PG variations offers a new dataset for studying atmospheric electricity variations in suburban area in Central Europe and can potentially contribute to better understanding of local atmospheric Potential Gradient (PG) variability and their linkages with Global Electric Circuit (GEC) characteristics.

## AS25-0801

# Observation and simulation of Schumann resonances near Nizhny Novgorod

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The interest of researchers in exploring the alternating current global electric circuit (AC GEC), associated with Schumann resonances (SR)—the modes of the Earth-ionosphere cavity excited by lightning discharges—and its potential connections to various scales of atmospheric variability remains strong. Variations in both the amplitude and frequency of SR harmonics have been observed across multiple timescales, including diurnal and seasonal cycles, as well as during El Niño episodes, reflecting changes in lightning activity dynamics.

Here we present new SR observations obtained from continuous measurements (2023–2024) using two orthogonal coil induction magnetometers in a rural location near Nizhny Novgorod, Russia (56°31′23″N, 43°47′56.91″E), largely free from anthropogenic electromagnetic noise. The low noise level enabled us to record the temporal dynamics of the first two SR harmonics. Our observations clearly demonstrate diurnal variations in both the amplitude and frequency of these harmonics.

To further investigate the AC GEC, we developed a semi-analytical model that incorporates real lightning data from the World Wide Lightning Location Network (WWLLN) as sources and is capable of resolving SR spectrum dynamics with hourly resolution. This approach enabled us to compare and validate our measurements by modeling the electromagnetic fields precisely at the observation point.

The measurements were carried out within the framework of the RSF project 23-17-00264.

## AS25-0812

# Patterns of atmospheric variability on different timescales and the direct current global electric circuit

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The ionospheric potential (IP), being the sum of contributions from electrified clouds all over the globe, is arguably the most fundamental characteristic of the direct current global electric circuit (GEC) intensity. The IP variation on different timescales reflects global changes in the distribution of electrified clouds, which, in turn, are closely associated with the dynamics of deep convection. This motivates the search for patterns in the GEC variation which would reflect various modes of atmospheric variability. Here we report recent progress in this direction, primarily focusing on our own findings based on the results of long-term IP simulations involving the Weather Research and Forecasting model and the results of long-term surface potential gradient (PG) measurements at the Vostok station in Antarctica. We will discuss the effect on the GEC of the El Niño—Southern Oscillation (ENSO) and Madden–Julian oscillation (MJO), demonstrating statistically significant changes in electrical parameters between El Niño and La Niña years and over the eight traditionally distinguished phases of the MJO. Simulations clarify how changes in global convection patterns eventually result in the patterns observed in the simulated IP and measured PG. A particular attention will be given to the seasonal variation of the GEC, which is known to be difficult to infer from both measurements and modelling, as different data sets contradict each other. We shall try to reconcile various observations and simulations by taking into consideration local effects, diurnal changes in GEC parameters and the seasonal cycle of global insolation.

## AS25-0826

# High frequency induction coils at Eskdalemuir Observatory, UK for ELF research

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Induction coils permit us to measure the very rapid changes of the magnetic field at frequencies between 0.1 and 1000 times per second. Two horizontal induction coils have been in operation at Eskdalemuir Observatory (55.3° N, -3° E) since 2012, accumulating more than a solar cycle worth of measurements at a cadence of 100 Hz. The data have been used to study lightning intensity variation, pulsations, Schumann resonances and Ionospheric Alfvén Resonances. In 2024, the original refurbished CM11 coils and electronic system had reached their end-of-life and were replaced with MFS05 supplied and calibrated by GFZ at Niemegk. The MGS05 coils were paired with a Mingeo ObsDAQ and MagRec 5C recording system and deployed at Eskdalemuir in August 2025 running at 128 Hz. We describe the site, updated instrumentation and compare performance to the previous installation, showing the consistency between the two different systems.

## AS25-1030

# Simulation of a kinetic plasma instability in sprite streamers

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We have supplemented the Particle-In-Cell code SMILEI with the module for collisions between charged and neutral particles. The code has been evaluated and used for the examination of the nonlinear stability and dynamics of plasma in conditions of Transient Luminous Events, namely sprites. The linear kinetic instability, identified for filamentation of sprite streamers in J. Błecki and K. Mizerski [Archives of Mechanics, 70, 535–550, 2018], was simulated. The results strongly suggest that the instability cannot occur in sprite streamers and that the authors' assumption on quasi-stability of the drifting Maxwellian distribution does not hold. The code could be used for any kinetic weakly-ionized plasma simulation which concerns collisions between charged and neutral particles.

## AS25-1136

# Potential gradient as a proxy for anthropogenic air pollution in Sao Paulo, Brazil

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This study investigates the relationship between potential gradient (PG) variations and atmospheric pollution in São Paulo, Brazil. PG measurements were recorded using a BOLTEK EFM-100 sensor installed at the Center for Radio Astronomy and Astrophysics Mackenzie, covering the period from 2017 to 2024. PG values were compared with CO, PM10, SO2, NO, NO2, and NOx concentrations obtained from a monitoring station located 2 km away. PG data were analyzed under fair weather conditions, i.e., excluding periods with rain precipitation and thunderstorms. Preliminary results in some case studies suggest a strong correlation (~0.80) between PG and PM10 during winter, based on Pearson and Spearman correlation analyses. On the other hand, during summer there is a weak correlation between PG and PM 10 (~0.30), while other aerosols appear to show a higher correlation (~0.60). Additionally, a study of the daily variation during weekdays and weekends highlights high aerosol concentrations and PG amplitudes from Monday to Friday, indicating a strong link with anthropogenic activity. These findings reinforce the potential of PG as a proxy for air pollution in urban environments, supporting its role in atmospheric electricity studies and environmental monitoring applications.

## AS25-1245

# Long term monitoring of ULF-ELF band by Finnish pulsation magnetometer network

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Finnish pulsation magnetometer network has long-term ULF-ELF observations by induction coils started in the 1960's by the space physics research group of University of Oulu. The network has gone trough two major upgrades increasing band-width coverage and sensitivity during the digital era started in mid 1990's.

The first Schumann resonance mode monitoring is done since 2002 by induction coil magnetometers having 3 dB cut-off at 10 Hz with the sampling rate of 40 Hz. To improve signal noise ratio the system was redesigned from the preamplifiers to data sampling. The band-width was lifted up to cut-off 35 Hz and the sampling rate to 250 Hz. Also timing accuracy was improved to use 10 MHz GPS reference making the network coherent. Today the network includes 8 stations covering L-shells 3.4 to 6.5 at the magnetic meridian range 101–108° E. Part of the network is still operated with older 40 Hz instrumentation.

The pulsation magnetometer network is traditionally used for studies of geomagnetic pulsations and EMIC-waves. The first Schumann resonance is continuously measured since 2002 with high data coverage rate over 20 years. The analysed Schumann resonance time serie is presented as well the detection results of arrival direction of the Hunga-Tonga eruption based on to the properties of the polarisation ellipse.

In addition the Finnish pulsation magnetometer network has been part of the PITHIA-NRF TNA program. Analysis of strong transients was started in November 2024 during a TNA visit. The detection sensitivity of strong transients by the Finnish pulsation magnetometer network is compared with Horsund induction coil data and WWLLN data sets.

## A12 Coupling Processes in the Atmosphere-Ionosphere System

### AS25-0018

# Chemical Heat Derived from Rocket-Borne WADIS-2 Experiment

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In the mesopause, space meets the atmosphere, therefore, the energy balance of this region is very complex, as some of the energy comes from above, some from below and some is generated internally. The information about energy balance is fundamental to understand the coupling processes in this region. One of the essential sources of energy in the mesopause is chemical heat released from exothermic reactions.

In our work, chemical heating rates were derived from three of the most significant reactions based on the analysis of common volume rocket-borne measurements of temperature, atomic oxygen densities, and neutral air densities. This is one of the first instances of the retrieval of nighttime chemical heat through the utilisation of non-emissive observations of atomic oxygen concentrations, obtained through in-situ measurements, performed at the Andøya Space Center (69° N, 16° E) at 01:44:00 UTC on 5 March 2015. We determine the heating efficiency for one of the most significant reactions of atomic hydrogen with ozone and illustrate the methodology for such calculations based on known atomic oxygen and temperature. Subsequently, using ozone values obtained from satellite observations, we retrieved odd-hydrogens and total chemical heat. Finally, we compared the retrieved chemical heat with the heat from turbulent energy dissipation. Our findings reveal that the vertically averaged chemical heat is greater than the heat from turbulent energy dissipation throughout the entire mesopause region during nocturnal conditions. The heating rates of turbulent energy dissipation may exceed the chemical heating rates only in narrow peaks, several hundred meters wide.

## AS25-0070

# Linkage between the major sudden stratospheric warming and sporadic E layer intensification in the winter of 2009

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This study provides a physical mechanism for the intensification of winter sporadic E layers (WiEsLs) in 2009. EsL intensity is known to be minimal in winter, partially because of weakened vertical wind shears. Despite the winter minimum of EsL intensity, intensification of EsLs occurred for 10–30 days in some winters, the cause of which remains unclear. In this study, we conducted month-long EsL simulations in 2009 and 2011, the years when both WiEsL intensification and sudden stratospheric warming (SSW) occurred, and when neither occurred, respectively. The simulations aimed to reveal the physical mechanisms of the WiEsL intensification in 2009. We succeeded in reproducing the occurrence and non-occurrence of the WiEsL intensification in 2009 and 2011, respectively, as observed by ionosondes in Japan, although day-to-day variations in the WiEsL intensity were not well reproduced. Evidently, the WiEsL intensification is attributed to the vertical ion convergence (VIC) intensification at altitudes of 100–120 km, especially after 15 LT. The VIC intensification is caused primarily by vertical wind shears of the intensified migrating semidiurnal tides. The major SSW in January–February 2009 drive the intensification of migrating semidiurnal tides. Our results show that the tidal variability due to SSW events can drive WiEsL intensification.

## AS25-0155

# Equatorial Plasma Density Irregularities Observed by Advanced Ionospheric Probe Onboard FORMOSAT-5 Satellite

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A FORMOSAT-5 satellite was launched on 25 August 2017 CST into a 98.28° inclination sun-synchronous circular orbit at 720 km altitude along the 1030/2230 local time sectors. Advanced Ionospheric Probe (AIP), a piggyback science payload developed by National Central University for the FORMOSAT-5 satellite, has measured in-situ ionospheric plasma concentrations at a 1,024 Hz sampling rate over a wide range of spatial scales for more than 7 years. In this presentation, global plasma density irregularities in the pre-midnight sector had been seasonally selected from FORMOSAT-5/AIP data during 2018 to 2024. Annual variations of these irregularity patterns with solar cycle could be clearly observed and compared with those by Ionospheric Plasma and Electrodynamics Instrument (IPEI) onboard ROCSAT-1 satellite last two decades ago.

## AS25-0161

# Investigation of the upper atmospheric variability during sudden stratospheric warming (SSW) events over magnetic conjugate locations

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In this work, we first compared the Antarctic minor SSW of 2019 with the Arctic major SSW of 2013. Despite being minor SSW, the rare Antarctic event of 2019 caused significant enhancement of the stratospheric temperature at high latitudes, with more temperature deviation than the major Arctic SSW of 2013. Based on the duration and extent of stratospheric zonal mean zonal wind (ZMZW) the 2019 SSW is comparable to major SSWs, with an exceptionally strong wave 1 planetary wave. We have investigated ionospheric response during both the SSWs using total electron content (TEC) and foF2 over two low mid-latitude magnetic conjugate locations Okinawa (26.21°,127.68°,38°dip) and Darwin (12.46°,130.84°,39°dip). Prominent ionospheric fluctuations have been observed during both the SSWs with maximum deviations in their respective hemispheric station, with clear hemispheric asymmetry. Minor geomagnetic storm has been noticed coinciding with each SSW during different phases of the warming. The SSW, solar flux and storm contribution on the TEC have been calculated during both the SSWs, which shows clear contribution of SSW on the total TEC despite the presence of storm and during moderately high solar activity. In the second part, we investigated tidal variability in the mesosphere and lower thermosphere (MLT) during 2021 Arctic SSW using ground-based meteor radar wind observations in equatorial and extratropical stations. We have not observed any consistent response of the diurnal and semidiurnal tides at the observational stations, but the global reanalysis dataset shows significant and consistent variability in certain zonal wavenumber components.

## AS25-0167

# Vertical coupling between sudden stratospheric warming and the European mid-latitude ionosphere

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Climatologically, Stratospheric Polar Vortex (SPV) is a planetary-scale eastward circulation formed through radiative cooling and confined in polar hemispheres during their respective winter period. Occasionally, this climatological circulation in SPV undergoes perturbations due to enhanced planetary wave activity leading to Sudden Stratospheric Warmings (SSWs) characterized by a sudden temperature change and a deceleration or even reversal (eastward to westward) in zonal flow. However, the classical definitions for SSWs are constrained to 10 hPa (~30 Km) for specified reasons, limiting the ability of these definitions to capture the coupling between the upper stratospheric dynamics and the related effects in the upper atmosphere region. To analyze the plausible effects of upper stratospheric changes and related coupling in the upper atmosphere, we studied the 2005 -2006 SSW, focusing on the upper (1–5 hPa) and a part of the middle stratosphere (7 hPa and 10 hPa). Apart from the officially recognized warming episode on 21$^{st}$ January 2006, based on 10 hPa, we identified stronger warming episodes in the beginning and mid of January at the upper stratosphere. Following these observations, we search for the coupled effect of these early episodes on the critical frequency of the F2 layer (foF2) and Total Electron Content (TEC) available from European mid-latitude ionospheric stations, indicating non-typical ionospheric conditions.

## AS25-0215

# Ionospheric disturbances during geomagnetically quiet and disturbed periods; continuous Doppler sounding and airglow observations

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A propagation analysis of Travelling Ionospheric Disturbances (TIDs) observed by multi-point Continuous Doppler Sounding (CDS) system located in central Europe during geomagnetically quiet and disturbed periods is presented. It is shown that the direction of TID propagation changes during the day, mainly due to the effect of neutral winds. During geomagnetic storms, equatorward propagating TIDs (usually large-scale TIDs), are detected. First results obtained by a new CDS system that distinguishes polarization of the received sounding electromagnetic waves are also presented.

In addition, an example of atypical large scale north-westward propagating TIDs, which were observed over Argentina by simultaneous optical measurement of OI red- line (630 nm) emissions and multi-point CDS, is discussed. An origin (source) of these TIDs is currently unclear. On the other hand, TIDs of shorter periods/wavelengths are only observed by CDS, unlike these atypical TIDs and plasma bubbles. A likely explanation is that the positive and negative phases of TIDs with shorter wavelengths are cancelled during integration along the line of sight in a relatively thick OI 630 nm emission layer.

## AS25-0288

# Simulation Study of Plasma-Object Interaction: Applications to CubeSat Missions and Langmuir Probe Design

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Understanding plasma interactions is crucial for both spacecraft operations and in-situ plasma diagnostics. This study explores two applications of plasma-simulation techniques: CubeSat charging in lunar orbit and the design of multi-needle Langmuir probes (m-NLPs). First, we analyze how a CubeSat interacts with the dynamic lunar plasma environment, where transitions between the solar wind and Earth's magnetotail influence spacecraft charging and wake formation. Second, we examine how probe-plasma interactions affect current collection in m-NLPs, optimizing their design for accurate space plasma measurements. The insights gained from these simulations help refine instrument design and enhance the reliability of plasma measurements in space.

## AS25-0303

# Propagation characteristics of mesospheric gravity waves and medium-scale traveling ionospheric disturbances using multi-point airglow images at middle latitudes

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The airglow images at wavelengths of 557.7 nm and 630.0 nm visualize mesospheric gravity waves (GWs) at altitudes of 90–100 km and medium-scale traveling ionospheric disturbances (MSTIDs) at altitudes of 200–300 km, respectively. The 3-dimensional Fast Fourier Transform (3D-FFT) analysis technique is useful to extract propagation characteristics of GWs and MSTIDs from large-amount of airglow images. However, such 3D-FFT analysis of long-term airglow image data has been applied only to a limited number of stations. In this presentation, we report our recent results on 3D-FFT analysis of long-term airglow image data obtained at Hawaii (Naito et al., JGR, 2022, https://doi.org/10.1029/2022JA030346), at Darwin, Australia (Tsuboi et al., JGR, 2023, https://doi.org/10.1029/2022JA030769) and at Sata, Japan (Tsuboi et al., JGR, 2023, https://doi.org/10.1029/2023JA031600). These results indicate that tropospheric convection and mesospheric jet play an important role in GWs in the mesopause region. The propagation direction of mesospheric GWs tends to be poleward in summer at all these three stations. The power spectrum density of MSTIDs in 630.0-nm images increases during low solar activity periods, suggesting suppression of mid-latitude ionospheric instabilities during the solar maximum.

## AS25-0306

# Chemical Equilibria and Characteristic Times during SSW Events

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Atomic oxygen is a critical species in the mesopause region, governing the chemistry, airglow, and energy budget (taking part in exothermic chemical processes and microwave cooling processes). It participates in plasma-chemical reactions in that region. Hence, it is involved in the coupling between dynamics and chemistry, plasma and neutral chemistry. However, it cannot be measured directly by satellite remote sensing techniques, so inference techniques from airglow observations are used. Such techniques are based on the assumption of ozone photochemical equilibrium.

Sudden Stratospheric Warmings (SSWs) provide us with a natural test of our understanding of the processes occurring in the middle atmosphere. With 3D modelling we find that ozone strongly deviates from photochemical equilibrium in the mesopause region during SSW events and nighttime conditions. The lower boundary of ozone equilibrium jumps up to a height of 90 km, implying that traditional techniques for retrieving atomic oxygen, atomic hydrogen, and chemical heat from airglow observations cannot be applied at times of SSWs below 90 km at nighttime. We discuss and explain our result in terms of characteristic times. Additionally, in order to gain inside in the exothermic chemical heat behavior, we calculate odd-hydrogens photochemical equilibria and characteristic times, which are involved into exothermic chemical reactions.

## AS25-0313

# Sporadic-E layer responses to super geomagnetic storm 10–12 May 2024

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Sporadic E (Es) layer plays a prominent role in revealing both upward and downward atmosphere-ionosphere coupling process. This study investigates the responses of Es layers to the May 2024 super geomagnetic storm by using 37 ground-based ionosondes distributed globally and space-based COSMIC-2 radio occultation observations. The results show that Es layers were significantly enhanced during the recovery phase of geomagnetic storm. In addition, the enhanced Es layers mainly occurred over Southeast Asia, Australia, the South Pacific and the East Pacific. The temporal evolution of foEs disturbances over the Asian-Australian sector clearly shows the "wave propagation" characteristics from high to low latitudes, indicating that the enhancements of the Es layers are most likely caused by the disturbed neutral winds in the E region. This study presents observational evidence for the downward impacts of the geomagnetic storm on the E-region ionosphere.

## AS25-0411

# Quasi 6-Day Planetary Wave Oscillations in Equatorial Plasma Irregularities

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The influence of atmospheric planetary waves on the occurrence of irregularities in the low latitude ionosphere is investigated using Whole Atmosphere Community Climate Model with thermosphere- ionosphere eXtension (WACCM-X) simulations and Global Observations of the Limb and Disk (GOLD) observations. GOLD observations of equatorial plasma bubbles (EPBs) exhibit a ∼6–8 day periodicity during January–February 2021. Analysis of WACCM-X simulations, which are constrained to reproduce realistic weather variability in the lower atmosphere, reveals that this coincides with an amplification of the westward propagating wavenumber-1 quasi-six day wave (Q6DW) in the mesosphere and lower thermosphere (MLT). The WACCM-X simulated Rayleigh-Taylor (R-T) instability growth rate, considered as a proxy of EPB occurrence, is found to exhibit a ∼6-day periodicity that is coincident with the enhanced Q6DW in the MLT. Additional WACCM-X simulations performed with fixed solar and geomagnetic activity demonstrate that the ∼6-day periodicity in the R-T instability growth rate is related to the forcing from the lower atmosphere. The simulations suggest that the Q6DW influences the day-to-day formation of EPBs through interaction with the migrating semidiurnal tide. This leads to periodic oscillations in the zonal winds, resulting in periodic variability in the strength of the prereversal enhancement, which influences the R-T instability growth rate and EPBs. The results demonstrate that atmospheric planetary waves, and their interaction with atmospheric tides, can have a significant impact on the day-to-day variability of EPBs.

## AS25-0429

# Development of a Neutral Mass Spectrometer for Ionospheric Observations and Initial Results of a Sounding Rocket Observation

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Collisions between plasma and neutral particles are the essential feature of Atmosphere-Ionosphere coupling. The collisions directly affect plasma motions and, eventually, influence ionospheric electrical conductivities. The collision frequency depends on the species of the colliding particles. Therefore, the composition of the neutral atmosphere is necessary for analysis of various ionospheric phenomena. While the neutral composition at ionospheric altitudes was often observed by a mass spectrometer on sounding rockets and artificial satellites from the 1950s to the 1980s, few observations have been recently made because some empirical models have been developed and improved. However, in-situ measurements are still desired, for example, to get higher spatial resolution data, and to validate empirical models. We have developed a neutral mass spectrometer small enough to be mounted on JAXA's S-310 sounding rocket to increase the opportunities for direct observations of the neutral atmospheric composition. The instrument uses time-of-flight mass spectrometry equipped with three-time reflections to reach a high mass resolution of more than 200 with a size of 156×187×130 mm without an intake. This device will be installed on S-310-46 sounding rocket launched this summer. The rocket experiment is named 'RIDE campaign' (Rocket Investigation of Daytime sporadic-E campaign) and aims to elucidate the developmental process of daytime sporadic E layers. The mass spectrometer will provide the density profile of the major components, such as O,N2, and O2, from 90 km to 130 km. The details of the instrument and, if possible, the initial results obtained in RIDE campaign will be included in the presentation.

## AS25-0439

# The X-pattern Merging of the Equatorial Ionization Anomaly Crests

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A unique and unexpected phenomenon—merging of Equatorial Ionization Anomaly (EIA) crests, leading to an X-pattern—has been observed in the night-time measurements by the Global-scale Observations of the Limb and Disk (GOLD) mission. The EIA X-pattern is observed to occur occasionally within the GOLD's field-of-view. The pattern persists for the duration of GOLD's post-sunset observations at longitudes from western Africa to western South America, ~3, hours with or without any significant longitudinal movement. A whole atmosphere general circulation model simulation produces a similar EIA X-pattern. The pattern is also observed in a global assimilative ionosphere model that assimilates Global Navigation Satellite System Total Electron Content (GNSS-TEC). The pattern can occur more frequently during solar minimum compared to solar maximum conditions. We explain this enigmatic phenomenon with the help of the experimental observation, numerical model simulation, and data assimilation results.

## AS25-0461

# Effects of increased solar activity and solar storms on the E-layer ionosphere in the European sector

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Recently, we have been experiencing an unexpectedly high solar maximum. In particular, during May 2024, a series of geomagnetic storms occurred after the Sun produced multiple intense solar flares and coronal mass ejections. This period is considered the most powerful storm affecting the Earth since March 1989.

In this study, we focus on the impact of the increased solar activity and especially on solar storm events on the E-layer ionosphere in the European sector. We are using ionosonde and GNSS radio occultation measurements to observe the unusual behavior of sporadic E layers. A special type of sporadic E layer, known as the auroral type or Esa type, usually forms during times of particle influx in the auroral region. The Esa type can be identified in ionograms as diffuse traces not blanketing the F-region.

During the storms, we observed the Esa type in central Europe, coinciding with polar light displays. The radio occultation SNR profiles recorded in similar regions showed exceptionally high background noise. Additionally, the sporadic E occurrence rate and intensity strongly increased during and slightly after the storm period, especially in the auroral region.

## AS25-0479

# Atmospheric tidal variability in the mesosphere and lower thermosphere as derived from the the JAGUAR-DAS Whole neutral Atmosphere Reanalysis (JAWARA)

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The JAGUAR-DAS Whole neutral Atmosphere Reanalysis (JAWARA) is the first long-term reanalysis of the neutral atmosphere extending from the surface to the lower thermosphere. Using hourly JAWARA data over the past two decades, this study examines variability of atmospheric tides in the mesosphere and lower thermosphere (MLT) region, which plays a significant role in driving ionospheric variability. We will demonstrate how tidal activity in the MLT region correlates with variations in the lower atmosphere, highlighting examples such as the semidiurnal tide response to Arctic sudden stratospheric warmings (SSWs). Following the occurrence of major SSWs, the amplitude of the semidiurnal tide increases and the phase becomes more antisymmetric about the equator, which can be well represented by the enhancement of the antisymmetric (2,3) Hough mode of classical tidal theory.

## AS25-0534

# Sporadic E occurrence during geomagnetically quiet time

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The ionosphere is a highly variable system. It responds both to forcing from above (solar and magnetospheric activity) and from below to processes in the entire lower atmosphere. It is a transition region between the neutral atmosphere and the fully charged plasmasphere. The ionospheric E region represents a plasma in which collisions of ions with neutrals play an important role. The motion of charged particles across the magnetic field leads, under favourable conditions, to convergence in the thin layers known as sporadic E (Es). During geomagnetically quiet periods, the effects of lower atmospheric forcing are more pronounced and can be studied in detail. In this study, we focus on the variability of the Es layer above middle latitudes during the summer season under low geomagnetic and stable solar forcing. In particular, we analyse the occurrence of the layer, its stratification and layer type in relation to the tropospheric mesoscale convective systems. Sporadic E-layer structures reflect the upward propagating gravity waves generated by the severe weather phenomena. We include in the study data from the European sector.

## AS25-0612

# Tidal Control of Ionospheric Electrodynamics

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Atmospheric tides are the dominant dynamical process in the mesosphere and thermosphere. Observations and modeling studies have shown that they can significantly impact the ionospheric wind dynamo and the space weather at low latitudes. This talk will focus on two aspects of the tidal control of the ionospheric electrodynamics: (1) The day-to-day variability—i.e. the weather—of the tides and its connection with that of pre-reversal enhancement (PRE) under solar maximum conditions; (2) The connection between tides and the midnight upward drift (MUD) under solar minimum conditions. It is shown that the PRE and the MUD from WACCM-X simulations show seasonal and longitudinal variations similar observed drifts. Furthermore, these PRE and MUD variations are also similar to the occurrence frequency of equatorial plasma bubbles (EPBs) during post-sunset and post-midnight periods, respectively. Such similarity suggests the key role of large-scale ionospheric electrodynamics, which is in turn strongly controlled by tides, in driving EPBs under different solar conditions.

## AS25-0711

# Persistent solar wind driving of the high-latitude ionosphere during winter night conditions

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The modelling and prediction of ionospheric storm effects driven by solar wind are still a challenge for the research community. Recently, it has been shown that there exists a persistent modulation of the high-latitude ionosphere with the solar wind variability. Here, we are investigating the potential source mechanisms of the persistent ionosphere modulation during winter night conditions. We use a set of ionosphere observations (EISCAT, IGS Total Electron Content, Tromso ionosonde) as well as AISstorm, a high-resolution numerical model for the simulation of atmospheric ionization rates caused by precipitating particles. For the approximation of the solar wind energy into the Earth system, we compute the Kan-Lee merging electric field Em provided by OMNI. We study the correlation and time lag between the variability of Em and the ionospheric parameters and characterize the spatial extent of the regions with highest solar wind correlations.

A correlation of ionospheric parameters and Em is present in both, the E- and F-region during winter night condition. The time lag in the E-region (45–90 minutes) is smaller than in the F-region (90–135 minutes). Both, precipitation effects and plasma convection can be observed during the EISCAT campaigns. The region with the highest correlation extends along the auroral oval. The temporal and spatial occurrence agrees well with the occurrence of E- and F-region precipitation reproduced by AISstorm. We conclude that both, precipitation and plasma convection effects, are major contributors to the modulation of the high-latitude ionosphere observations with solar wind variability.

## AS25-0781

# High-frequency wave interactions with topside ionospheric density irregularities

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Ionospheric modification experiments show that geomagnetic field-aligned irregularities can direct high-frequency ordinary (O)-mode pump waves beyond their reflection layer in the bottomside ionosphere, enabling them to reach higher altitudes. The subsequent interaction of the waves on the topside is vital for determining whether wave energy is confined in the ionosphere or escapes. We used the finite-difference time-domain (FDTD) method to investigate wave behavior near the topside plasma resonance in a magnetic field-aligned density duct. We varied the angle between the magnetic field and the pump wave to examine how it influences wave transmission. Our results indicate that while the topside irregularities can also allow wave transmission through the plasma resonance, the magnetic aspect angle there is more sensitive than on the bottomside. This heightened sensitivity reduces transmission and increases absorption, manifested as strong Langmuir wave excitation. We attribute these effects to wave propagation characteristics in overdense magnetized plasma. We also discuss the implications of our findings for magnetic zenith effects observed in polar ionospheric regions.

## AS25-0967

# Multi-instrument analysis of TIDs generated by an intensive jet-front system with severe convection over Europe in August 2023

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Intense tropospheric events (e.g. jet-front systems and deep convection) can cause atmospheric gravity waves (AGWs) that, propagating upward, can reach the thermosphere-ionosphere system and cause wave-like oscillations known as travelling atmospheric/ionospheric disturbances (TADs/TIDs). The main purpose of the present study is to investigate TID activity occurred during a jet-front system accompanied by intense convection that passed through continental Europe between 25 and 29 August 2023. During the event, the geomagnetic activity can be considered as calm. Several observational techniques were used during the study: vertical ionospheric soundings at seven European ionosonde stations, the Continuous Doppler Sounding System (CDSS) in Czechia, and Total Electron Content (TEC) measurements provided by ground-based Global Navigation Satellite System (GNSS) receivers co-located with the ionosondes. The most intensive TID activity was observed in ionograms, in the single station detrended TEC measurements, and in the CDSS records during the daytime on 27 August, when the jet stream reached its highest velocities (~ 200 km/h) over continental Europe. Signatures of TIDs were also observed during other analysed time periods which coincided with local thunderstorms and a Mesoscale Convective System (MCS) event. The dominant periods of the observed disturbances varied between 15 and 70 minutes.

## AS25-0984

# Orographic wave activity at mesospheric altitude over the Southern Ocean islands observed by the Atmospheric Waves Experiment

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A major source for the gravity waves (GW) measured in the stratosphere and higher is the orographic forcing produced by the tropospheric wind blowing over mountainous regions. Recent studies have shown that even small islands can generate waves which, under appropriate conditions, are able to penetrate above 80 km altitude, transporting large amount of momentum into the upper atmosphere. Investigating the exact effects of those islands is challenging because ground-based and even airborne measurements are limited above those generally isolated places.

The Utah State University (USU) Atmospheric Waves Experiment (AWE) was designed and built to study mesospheric GW globally, even over inaccessible locations. This NASA-funded mission deployed an infrared imager on the International Space Station (ISS) in late 2023. It has been continuously taking images of the OH airglow layer every 1.1 s, over a 600-km radius, with a 2-km horizontal resolution, since November 22, 2023.

This presentation will describe AWE measurements of island-generated orographic waves around 87 km altitude. Numerous mountain wave observations have been obtained during the Austral winter 2024. The conditions for their deep propagation will be investigated using the NAVy Global Environmental Model (NAVGEM) to understand their intermittency, and their effects on the upper atmosphere.

## AS25-1017

# ENSO variations and CO2 abundance exchange between ocean and air

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We investigated a connection of the Oceanic Niño Index (ONI), or El Nino Southern Oscillation (ENSO) index in 1950–2023 with measurements of carbon dioxide CO2 by applying the wavelet spectral transform and the IBM SPSS correlations analysis. The ENSO index is found to have a strong (>87%) correlation with the Global Land-Ocean Temperature (GLOT). The wavelet analysis allowed us to detect the two key periods in the ENSO (ONI) index: 4–5 years and 12 years. The possibility of the volcanic eruptions causing ENSO discovering that the underwater volcanic eruptions induced by tidal forces of Jupiter and Sun can be the essential additional factors imposing the ENSO (ONI) index variations.

In addition, we explore the relatively persistent $CO_2$ sink in the Pacific Ocean surrounding the NOAA Global Monitoring Laboratory (GML) in Samoa and the GML on Mauna Loa on island of Hawaii, by comparing the CO2 datasets, running their spectral and correlational analysis in comparison with the relevant terrestrial parameters (ENSO, sea and air temperature). The $CO_2$exchange rate between the ocean and air since measurements began show a persistent offset between these two GMLs. Samoa GML reports negative 3 parts per million (ppm) relative to Mauna Loa but is surrounded by warmer tropical ocean where $CO_2$ emissions might be expected to be positively offset versus Mauna Loa. This situation is evaluated and compared to the increase of ENSO. The results are evaluated and discussed in relation to climate changes recorded in the recent centuries.

## AS25-1032

# Examining the Impact of Thunderstorm-Induced Gravity Waves on Low-Latitude Ionospheric Dynamics

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This study explores coupling processes between the lower atmosphere and the ionosphere induced by thunderstorm activity, utilizing comprehensive ground-based and satellite observations from the IISC00IND GPS station at the Indian Institute of Science (IISc), Bangalore. Emphasizing lightning events under geomagnetically quiet conditions, significant ionospheric disturbances associated with thunderstorms have been identified and characterized. Two notable events exhibited distinct Vertical Total Electron Content (VTEC) fluctuations: Event 1 showed variations between +0.32 and -0.41 TEC units with a temporal delay of approximately 120 minutes, while Event 2 demonstrated stronger fluctuations ranging from +1.21 to -1.12 TEC units, delayed by approximately 150 minutes. Concurrent temperature profiles from the SABER instrument revealed clear wave signatures with vertical wavelengths of 12 km and 21 km at around 80 km altitude, respectively. Complementary wave-like oscillations in TEC were detected at ionospheric heights (~300 km altitude), displaying vertical wavelengths of 42 km and 32 km, consistent with gravity wave propagation dynamics. Strong correlations between lightning occurrence and Atmospheric Gravity Wave (AGW) signatures were observed, highlighting direct coupling processes linking convective systems in the lower atmosphere to ionospheric perturbations. An expanded analysis encompassing eight thunderstorm events consistently showed ionospheric responses with temporal delays ranging from 38 to 180 minutes, underscoring the systematic nature of these atmospheric-ionospheric coupling processes.

## AS25-1084

# Analysis of CIR/HSS effects in the ionosphere over central Europe

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Co-rotating Interaction Region (CIR) and High-Speed Stream (HSS) driven storms are known to cause significant perturbations in the thermosphere-ionosphere system, manifesting as phenomena such as Travelling Ionospheric Disturbances (TIDs). We present an analysis of Digisonde measurements from the Pruhonice station in Czechia during CIR- and HSS-driven geomagnetic storms occurring during the solar cycle minimum years of 2019 and 2020. We focus on changes in electron density profiles and their derived parameters, such as foF2 and hmF2 as well as the analysis of sporadic E (Es) data. We also provide the classification of TID types based on the shape of the ionospheric reflection traces. The analysis is complemented by results from the Continuous Doppler Sounding System (CDSS) and Total Electron Content (TEC) measurements.

## AS25-1130

# Mesospheric Gravity Waves observed by NASA Atmospheric Waves Experiment (AWE)

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Although smaller scale gravity waves (GWs) (horizontal wavelengths ~30–300 km) are thought to account for the dominant energy and momentum inputs at the Ionosphere-Thermosphere-Mesosphere (ITM) altitudes, the sources, variability, and influences of these smaller-scale GWs are still major unknowns. The NASA Atmospheric Waves Experiment (AWE) is designed to measure these GWs in the mesopause region. In November 2023, AWE was successfully launched and deployed on the International Space Station (ISS) and science data collection was started. The AWE instrument maps the nighttime hydroxyl (OH) layer (~87 km), providing 2D GW fields in mesospheric temperature and OH band intensity over a 600 km field-of-view, every second.

This presentation will utilize the first year of AWE measurements to investigate the global distribution of GWs and their seasonal, hemispheric characteristics in the mesosphere. Model results (WACCM-X and NAVGEM) will be utilized to investigate the wave propagation conditions and possible sources in the lower atmosphere.

## AS25-1287

# An introduction to Keystone: a potential ESA Earth Explorer 12 Mission

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Keystone is one of four mission concepts selected for assessment study as a potential mission for ESA's Earth Explorer 12. It addresses gaps in the least understood region of the atmosphere, the mesosphere and lower thermosphere. Observations in spectral windows in the Terahertz (THz), infrared (IR) and visible / ultraviolet (UV-Vis) regions of the electromagnetic spectrum target the observations of atomic oxygen, composition, temperature and wind in the mesosphere and lower thermosphere. These observations provide information which will narrow the significant gaps in our knowledge of the constituent and thermal budgets at these heights and identify the underlying dynamical and chemical processes. Knowledge of atomic oxygen is key to this mission because of its role in these budgets and its value as a conserved tracer in the lower thermosphere. The mission concept is currently being developed through an assessment study undertaken by a Mission Advisory Group (co-authors above) led by Daniel Gerber and supported by an ESA Core Team. This talk will present the mission objectives, and the scientific questions Keystone will address.

## AS25-1334

# Dynamical signatures in nightglow: interpretation and examples

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Nightglow has been used as a means to diagnose wind, temperature and wave characteristics for many years. All sky images provide information on the wave morphology in the mesopause regions and hence contextual information for single point measurements provided by other techniques such as radar, lidar and interferometers. Less attention has been paid to the implications of the magnitude of the observed nightglow variability. In this paper, the dependency of the brightness on the atomic oxygen profile, vertical advection and mixing are discussed. Links between airglow, chemical heating, and mixing in the mesosphere and lower thermosphere are also noted. Observations of wave effects (including perturbations associated with the Hunga Tonga eruption seen in the high Arctic mesosphere and lower thermosphere) on airglow variability, temperature and wind are presented and interpreted in terms of this framework.

# A13 Middle and upper atmosphere: From solar variability influence to long-term changes

## AS25-0013

## Lower Atmosphere Variability: A Driver of Delayed Ionospheric Response to Solar Activity

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Ionospheric irregularities are variations in plasma density that can, among others, significantly affect the reliability of Global Navigation Satellite Systems. Therefore, understanding the underlying processes of these irregularities is crucial. These irregularities can be influenced by various external factors, including solar activity, geomagnetic disturbances, and lower atmospheric forcing. This emphasizes the need for their continuous monitoring and analysis. This study aims to investigate the impact of lower atmospheric forcing on upper atmospheric variability using the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM). We conducted numerical experiments to compare the variability induced by tidal Hough Mode Extensions (HME), which are constrained by winds and temperatures from observations made by the Ionospheric Connection Explorer-Michelson Interferometer for Global High-Resolution Thermospheric Imaging (ICON-MIGHTI). Our model comparisons focus on changes in the composition of the thermosphere-ionosphere and the delayed response of the ionosphere to the 27-day variations in solar EUV flux during periods of low solar activity. We report the results of model simulations with and without tidal forcing at the 97 km lower boundary of the TIE-GCM. The results show that tidal forcing primarily impacts low- and mid-latitude regions, altering the correlation of the atomic oxygen to molecular nitrogen ratio $O/N_2$ with the maximum electron density NmF2, which in turn affects ionospheric delay.

## AS25-0041

# Towards the Long-Term Trend Scenario in the Stratosphere-Mesosphere-Thermosphere-Ionosphere System

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Our knowledge of long-term trends has reached a level which allows us to create a joint scenario of global climate change in the stratosphere-mesosphere-thermosphere-ionosphere system. The main driver of trends is the increasing concentration of anthropogenic $CO_2$ up to at least the lower thermosphere. In the stratosphere, mesosphere and lower thermosphere, the evolution of the stratospheric ozone concentration as a result of changing emissions of ozone depleting substances also plays an important role and some role is played also by methane and water vapor changes, while at higher altitudes, and in particular for the ionosphere, the secular change of the Earth's main magnetic field becomes important. The scenario of long-term trends will consist of trends in all main parameters, including temperature, circulation/winds, atmospheric waves, neutral atmosphere composition, neutral density, noctilucent clouds, and parameters of the ionosphere, particularly electron density and related quantities, and ion and electron temperature. The scenario of trends will be presented including interrelations among various parameters. Potential controversies and gaps in knowledge of long-term trends/climatic change will be identified. The scenario will also consider practical aspects of trends, such as their impact on the future evolution of the amount of dangerous space debris at heights of typical satellite orbits.

## AS25-0092

# Long-Term Trends in the Ionospheric Equivalent Slab Thickness possibly associated with the Earth's Climate Change

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Anthropogenic greenhouse gas (GHG) emissions are the ongoing major driver of Earth's climate change. While the increasing concentration of GHG causes a warming of the lower atmosphere, it leads to a cooling of the upper atmosphere, which is expected to result in a thermal contraction. These changes in the neutral atmosphere have been demonstrated to also influence the ionosphere. Indeed, the contraction of the whole upper atmosphere induces a downward displacement of the ionospheric layers, due to the changes in the vertical distribution of the different ion species in the ionosphere.

To study the ionosphere changes in response to climate change, we investigated the long-term trends of the ionospheric equivalent slab thickness (τ). τ represents the thickness of an ideal ionospheric slab of constant electron density equal to that of the F2-layer peak (*Nm*F2) with a vertical total electron content (vTEC) value equivalent to that of the entire ionosphere. To achieve this, τ time series have been derived from a selection of globally distributed and co-located ionosondes (providing *Nm*F2) and GNSS receivers (providing vTEC), focusing on stations with at least two solar cycles of continuous data. For trend and coherent structures extraction and analysis, we use the Empirical Mode Decomposition (EMD), an advanced data-adaptive decomposition method. EMD is particularly suited for preserving nonlinearity in time series and for processing non-stationary data, offering a more accurate representation of long-term variations compared to traditional statistical methods. Preliminary results will be presented here and associated with the existing literature on the topic.

## AS25-0177

# Long term reduction of F2 layer peak electron density at mid-latitudes

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The talk focuses on studying long-term trends of the F2 layer peak electron density (NmF2) derived from vertical sounding measurements at 10 ionosonde stations situated in mid-latitudes at European, Asian and American longitude sectors. The ionosonde data cover a time period of 71 years thus fulfilling an important condition for long-term trend (LTT) studies. To derive long term changes of the behavior of NmF2measurements around noontime, its relationship with the solar 30 cm radio flux index F30 has been investigated. Confirming earlier results, the long-term behavior of 11 years sliding averages of NmF2 data shows a substantial decrease from reference values. The reference level, specific for each ionosonde station, is defined by a linear model of noontime NmF2 averages as a function of the F30 solar index. Whereas the 11 years running average values of NmF2 are proportional to corresponding F30 values within a small variability range of less than ±1% until 1985, NmF2 decouples substantially from this linear relationship with F30 at ionosonde stations afterwards. The reduction of NmF2 may reach up to $1.6 \cdot 10^{11} m^{-3}$ or about 20% referred to the linear model in 2022. The reduction is different at Northern and Southern hemispheres. The derived noticeable long-term trends of ionospheric peak electron density are assumed to be correlated with climate changes at the Earth surface due to greenhouse gases.

## AS25-0185

# Model-based analysis of ionospheric reaction to 27-day solar EUV variability—A long-term study

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Solar extreme ultraviolet (EUV) variability is a key driver of upper atmosphere ionization and as such has significant influence on ionospheric electron density and composition across multiple timescales. The 27-day solar rotation cycle is also reflected in the emitted EUV radiation and therefore also in many ionospheric parameters, such as total electron content (TEC). Superimposed on this pattern are additional long- and short-term trends and disturbances that further modulate the ionospheric plasma.

This study uses numerical simulations with the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), to examine the ionospheric response to various 27-day solar rotation periods and the response of the upper atmosphere. The Open Time-Series of the High-Resolution Ionosphere-Thermosphere Aeronomic Climate Simulation (OTHITACS) dataset is used, which is based on TIE-GCM. The OTHITACS dataset allows the analysis of ionospheric responses from 2000 to 2022 under varying solar activity levels and geomagnetic states. This study mainly focuses both on global and local TEC variations. Despite irregularities in the EUV profiles, a dominance of the 27-day rotation in the ionospheric plasma is observed, which was also demonstrated in previous studies on the delayed response. Furthermore, this study provides a 4D-analysis of the ionospheric reaction to solar EUV variability.

## AS25-0248

# Long term trends in the thermosphere and their impact on the future space debris environment

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Increasing carbon dioxide concentrations in the atmosphere have been shown to result in a reducing neutral density trend in the upper atmosphere. Objects in low Earth orbit (LEO) travel through the thermosphere experiencing atmospheric drag. Lower neutral densities result in less atmospheric drag, reducing the impact on orbits, with this phenomenon used to derive historic trends in neutral density. Numerical atmospheric models such as TIE-GCM and WACCM-X have also simulated these historic trends.

In this talk we look primarily to the future, and the impact a continuing reduction in neutral density will have on the objects in a future LEO environment. The future thermosphere has been simulated with WACCM-X under increasing carbon dioxide concentrations up to 900 ppm. Rather than look at trends in "% per decade" changes, instead future changes are tied to carbon dioxide concentrations, allowing the future thermosphere to be modelled under different CO2 scenarios, set out by the Shared Socioeconomic Pathways (SSPs) published by the Intergovernmental Panel on Climate Change (IPCC).

The impacts of these future density reductions upon the space debris environment in LEO are then explored under each SSP. Firstly, through the Binned Representative Atmospheric Decay (BRAD) model, we explore the possible evolution of the number of fragments and make-up of the LEO environment. Secondly, the MIT Orbital Capacity Assessment Tool (MOCAT) is used to show the total satellite-carrying capacity also reduces.

Finally, a newly available hourly resolution WACCM-X dataset covering 1950 to 2025 is introduced, and some initial results explored.

## AS25-0279

# Distinguishing the solar Gleissberg cycle from anthropogenic trends in the ionosphere

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Interest in upper atmosphere long-term trends began in the early 1990s. Since then over the years, ionospheric time series covering more than two solar cycles, necessary to adequately filter out the effects of solar activity, have become available. Some of them span over six decades now. However, a new challenge has emerged: solar activity also exhibits a weaker but longer quasi-periodicity of ~80–90 years, known as the Gleissberg cycle, and with time series now extending beyond 60 years this cycle is becoming evident. There is a limited knowledge regarding the adequacy of different solar EUV proxies over such long timescales due to the lack of data covering the full cycle. The available data indicate that while variations associated with the quasi-decadal solar cycle are similar across all proxies, those linked to the Gleissberg cycle are not, i.e. the differences between successive maxima and possibly the weaker last two minima. This study explores the differences in the Gleissberg cycle across various solar EUV proxies and examines their impact on the estimation of the residuals used to estimate ionospheric trends attributed to anthropogenic drivers as the increasing greenhouse gas concentration. An important result is that, depending on the proxy used, the estimated ionospheric trend can be null or even change sign, and the effect is sensitive to the selected time period for the estimation. While this issue overlaps with numerous existing studies on the most suitable proxy in ionospheric trend analysis, these results provide a new and valuable perspective.

## AS25-0286

# Identifying solar and anthropogenic contributions to the long-term variability of ionospheric equivalent slab thickness

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Based on the discussions and contributions of Working Team #1 within IAGA WGII-F, this study provides additional insights into long-term trends in the ionospheric equivalent slab thickness, a topic identified as requiring further investigation to clarify key aspects of the upper atmosphere trend analyses. Results from stations with the longest available data records and minimal gaps are presented. Our primary goal is to distinguish the effect of solar activity and to determine the residual trend that can be attributed to anthropogenic influences. This is particularly complex because slab thickness is the ratio of the vertical Total Electron Content (vTEC) and the peak electron density (NmF2), both of which depend strongly on solar activity. And, although the solar signal in this parameter is significantly reduced, it is not completely eliminated, and it even seems to deviate from the dependence observed in its individual components. On the basis of the dependence of vTEC and NmF2 on solar activity, a function is developed that is assumed to represent the solar effect in the slab thickness, and its residual is assumed to carry the trend of anthropogenic origin. Although most trends obtained are not statistically significant, and the time series may be too short to fully separate solar and anthropogenic effects, the proposed method remains valuable for isolating these influences in this particular and informative ionospheric parameter. In this case, modeling is also essential for trend drivers' distinction, hence modeled results are included.

## AS25-0304

# Solar cycle influence on mesosphere/lower thermosphere winds over Germany

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At Collm (51.3N, 13.0E) mesosphere/lower thermosphere wind measurements have been performed for more than four decades using Low-Frequency spaced receiver and Very High Frequency meteor radar observations. We analyse the combined time series with respect to long-term changes, in particular on the possible effect of an 11-year solar cycle. We find that in the 1980s and 1990s there is a negative correlation with solar EUV proxies in spring and early summer, with a weaker lower thermospheric jet during solar maximum. This correspondence weakens after year 2000. In winter, there is a weak positive effect towards stronger westerly winds during solar maximum. We compare these results with Partial Reflection radar observations of mesospheric winds over Juliusruh (54.6 N. 13.4 E) and also compare them with decadal variations of gravity wave proxies.

## AS25-0307

# Intra- and interannual variations of tides and planetary waves in the mid and high latitude MLT region

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Tide and planetary waves significantly influence the dynamics of the mesosphere lower thermosphere (MLT) and the residual mean meridional circulation in the middle and upper atmosphere. It is well established that the characteristics of these tides and waves vary due to changes in the background conditions of the middle atmosphere, which can occur on a day-to-day basis and seasonally, affecting the upward propagation. However, the interannual variability and dependency on solar activity of tides and planetary waves and their latitudinal variations are not well understood.

This study aims to explore the intra-, interannual, and solar activity dependencies of tidal subharmonics and planetary waves using long-term, high-resolution radar wind measurements. In this study, we analyzed hourly mean zonal and meridional winds collected from two primary sources: a partial reflection radar/medium frequency radar (PRR/MF radar) located in Andøya, Norway, and a multilink meteor radar from northern Germany, spanning the years 2005 to 2024 and 2005 to 2021, respectively. We estimated the amplitudes of the tidal and planetary waves using fast Fourier transform techniques. Additionally, wavelet analysis was applied to the amplitudes of these waves to investigate their intra-, interannual, and solar activity dependencies. We also examined the latitudinal dependencies of the tides and planetary waves. A detailed description of our results and scientific outcomes will be provided in this presentation.

## AS25-0316

# Has the relationship between ionospheric behavior and geomagnetic activity changed over the past five solar cycles?

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Long-term variations in the ionospheric and thermospheric responses to solar EUV radiation have been documented in numerous studies. Model simulations indicate that these long-term changes in the thermosphere may influence the intensity of the ionospheric relationship with geomagnetic activity (GA). This study investigates the relationship between GA and the peak electron density of the ionosphere (NmF2) and examines its consistency across different solar cycles to identify any observable long-term changes.

Hourly values of NmF2 from six midlatitude ionospheric stations are analyzed from 1964 to 2019. The residuals from a dedicated background model are analyzed for correlation with several GA indices to detect the ionospheric relationship with GA.

Kpm was identified as the most appropriate index, yielding the highest absolute correlation with the residuals of NmF2. The observed patterns align with the well-established storm-time characteristics at midlatitudes, showing a predominant negative response during summer morning hours and a positive response during winter afternoons. During summer conditions, a predominant negative association with GA, which exhibits sufficiently high correlations for statistical analysis. However, no significant long-term changes in the relationship between NmF2 and GA were identified within the Kpm range of 0–5. During winter conditions, the results show the well-known positive relationship with GA during daytime, but the variability is so strong that no significant correlation to GA indices can be found, and detection of long-term changes is not possible. Consequently, the long-term changes in the relationship between the ionosphere and GA reported in model-based studies cannot yet be confirmed by observations.

## AS25-0354

# The Role of the Solar cycle in Climate

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Weak secular variations in solar irradiance remain a topic of intense debate due to their potential significance in understanding the Sun's influence on climate. Given that the total energy reaching Earth from the Sun fluctuates by less than 0.1% over the 11-year solar cycle—and even less over longer time scales—it raises the question of how such minimal changes could drive large climate variability. However, space-borne Aura Microwave Limb Sounder (MLS) measurements of the Earth's middle atmosphere, as well as total and spectral solar irradiance (TSI and SSI), have been recorded covering solar cycles 24 and 25. While approximately 20 years of data may be insufficient to fully assess the impact of the 11-year solar cycle on Earth's climate, increasing evidence suggests that middle atmosphere tracers (such as ozone, CO, and $H_2O$) and atmospheric dynamics are strongly linked to solar cycle variations. In this context, observational evidences of middle atmosphere changes associated with the 11-year solar cycle will be discussed.

## AS25-0413

# Impact of increasing greenhouse gases on the ionosphere and thermosphere response to a geomagnetic storm

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The Community Earth System Model (CESM) Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (WACCM-X) is used to investigate how the ionosphere-thermosphere response to a geomagnetic superstorm changes with increasing greenhouse gases. Coupled CESM(WACCM-X) simulations are first performed following the Coupled Model Intercomparison Project Phase 6 Shared Socioeconomic Pathway 5–8.5 from 2000–2090. The May 2024 geomagnetic superstorm is then simulated in 2016, 2040, 2061, and 2084, corresponding to surface CO2 levels of 403, 500, 652, and 918 ppmv, respectively. The CESM(WACCM-X) simulations indicate that increasing levels of CO2 weakens the absolute neutral density response at 350 km. However, the relative response is increased with increasing levels of CO2, which is partly due to the decrease in the background neutral density. Due to a weaker response in thermosphere composition and meridional neutral winds, the ionospheric response also weakens with increasing levels of CO2.

## AS25-0561

# Wavelet phase coherence analysis applied to the virtual height of the ionosphere 2022 at Brazil

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The Earth's ionosphere is a complex system where important physical phenomena take place and it is an important layer for several human activities such as radio communication. In this work, we analyse the F10.7 flux index and virtual height of the ionosphere during the year 2022 to study the wavelet phase coherence and cross wavelet and investigate the periods where both variables are correlated. The results showed a good coherence between both time series at the 4–8 days and ~16 days periods. However, we noted that exist a phase difference between these variables at the 4–8 days where it is possible to observe an anti-phase relationships. These results are explained by some solar events that occurred during the year 2022, which corresponds to the ascending phase of the solar cycle. One of these events studied is the X1.5 class flare on 10 May, which caused the radio blackout in some parts of the planet.

## AS25-0752

# Evaluation of JAGUAR-DAS Whole Neutral Atmosphere Reanalysis winds with independent sounding rocket and meteor radar observations over a tropical site

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Recent decades witnessed significant advances in scientific understanding of the influence of lower atmospheric weather phenomena on near-Earth space weather. Together with improved, widespread observations of the upper atmosphere, long-term and reliable record of weather phenomena facilitated by reanalysis datasets have played a pivotal role in identifying atmosphere-ionosphere coupling mechanisms. The recently released JAGUAR-DAS Whole Neutral Atmosphere Reanalysis (JAWARA) dataset provides the first ever long-period reanalysis product encompassing the whole neutral atmosphere from surface to 110 km, making it ideal for atmosphere-ionosphere coupling studies. In this study, we evaluate the JAWARA datasets using independent Rohini 200 (RH 200) sounding rocket and meteor wind radar neutral wind observations from a tropical site Thumba (8.5ºN, 76.5ºE). Fortnightly vertical profiles of horizontal winds in the 25–65 km region from RH 200 rocket soundings during November 2002 to November 2007 and hourly horizontal winds in the 80–100 km region from meteor wind radar observation during June 2004 to December 2015 are used for the analysis. Our results indicate a very good association between JAWARA and RH 200 observations for the zonal component. A better correlation is observed for the mesosphere-lower thermosphere (MLT) winds between the meteor wind radar and JAWARA datasets. We further compare the amplitude of the Mesopause Semiannual Oscillation (MSAO) and highlight the similarities and differences. Finally, we use JAWARA data to examine how well the reanalysis dataset reproduces the dynamics of the low latitude middle atmosphere during northern hemispheric Sudden Stratospheric Warming events using 2005–06 and 2008–09 boreal winters as case studies.

## AS25-1023

# Link of the ENSO index with solar and volcanic activity and orbital motion

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n this paper, we present a spectral analysis of the El Nino Southern Oscillation (ENSO) index in 1950–2023. The ENSO index is found to have a strong (>87%) correlation with the Global Land-Ocean Temperature (GLOT). The scatter plots of the ENSO-GLOT correlation with the linear and cubic fits have shown that the ENSO index is better fit by the cubic polynomial increasing proportionally to a cubic power of the GLOT variations. The wavelet analysis allowed us to detect the two key periods in the ENSO (ONI) index: 4–5 years and 12 years.

The smaller period of 4.5 years can be linked to the motion of tectonic plates while the larger period of 12 years is shown to have a noticeable correlation of 25% with frequencies of the underwater (submarine) volcanic eruptions in the areas with ENSO occurrences. Not withholding any local terrestrial factors considered to contribute to the ENSO occurrences, we investigated the possibility of the volcanic eruptions causing ENSO to be also induced by the tidal forces of Jupiter and Sun showing the correlation of the underwater volcanic eruption frequency with the

Jupiter-Earth distances and with the Sun-Earth distances, induced by the solar inertial motion, in January, when the Earth is turned to the Sun with the southern hemisphere where the ENSO occurs. The underwater volcanic eruptions induced by tidal forces of Jupiter and Sun and the grand solar minimum (2020–2053) can be the essential additional factors defining the ENSO (ONI) index variations in the next 30 years.

## AS25-1079

# Variability of tides from meteor radar winds at Cachoeira Paulista, Brazil

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Atmospheric tides dominate the Mesosphere and Lower Thermosphere (MLT) dynamics and reveal seasonal, interannual as well as long term variability. In the present study, MLT wind data obtained between 1999 and 2018 from meteor radar observations at Cachoeira Paulista (22.7° S, 45.0° W), Brazil, have been used to investigate the behavior of the interannual variability in the diurnal, semidiurnal and terdiurnal tide amplitudes. The results show that monthly meridional amplitudes of the diurnal tide are greater during the westerly phase of the stratospheric quasi-biennial oscillation (QBO) at 20 hPa. The modulation of the diurnal tide amplitude by the QBO shows a quasi-decadal variation, in which its amplitude is larger in years of solar maximum. The semidiurnal amplitudes show a relationship with the QBO for altitudes above 90 km, whereas the terdiurnal tide variability did not show it. Both semidiurnal and terdiurnal amplitudes behavior indicated a weak relationship with the 11-year solar activity. The results are compared with midlatitude results using observations at Collm (51.3° N, 13.0° E).

## AS25-1092

# Global variability in the ionospheric TEC during X-class solar flares of Solar Cycle 24

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This study analyzes the spatial variability in solar flare-induced Total Electron Content (TEC) during all the 49 X-class flares that occurred during Solar Cycle 24. The global TEC data from 247 Global Positioning System (GPS) stations available at the International GNSS Service (IGS) network has been used as the prime dataset. Flare radiation variability is studied using high-resolution X-ray (0.1–0.8 nm) and Extreme Ultraviolet (EUV) fluxes (26–34 nm), from Geostationary Operational Environmental Satellites (GOES) and the Solar and Heliospheric Observatory (SOHO). For each flare event, stations in the sunlit hemisphere and satellites with elevation angles exceeding 50° were selected for the analysis. The background TEC values, estimated via curve fitting, are subtracted from the TEC series to extract the flare-induced variation in TEC (ΔTEC). ΔTEC values indicated a non-uniformity across different events, probably due to fluctuations in flare intensity. Moreover, elevated ΔTEC values were noted at locations adjacent to the subsolar point, attributed to the enhanced photoionization rate over the zenith atmosphere. Spatial maps for all 49 events demonstrated a radial decrease in ΔTEC, centered around the subsolar point. These findings highlight the significant role of solar zenith angle (SZA) in influencing flare-induced ionospheric response. To quantify this, the cosine of SZA has been plotted against ΔTEC. The ratio of ΔTEC at SZA = 90° to that at 0° varied from 0.13 to 0.87, with a mean of 0.45. The fluctuating ratio suggests that factors beyond SZA might also influence the ionospheric response to solar flares.

## AS25-1127

# Long-term Mesospheric temperature variabilities from southern hemisphere mid-and high-latitudes

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Decade-long datasets of mesospheric temperature measurements had been obtained since 2009 from two southern hemisphere sites. The USU Mesospheric Temperature Mapper (MTM) at the Andes Lidar Observatory, Chile (30° S) had been making OH (6,2) rotational temperature measurements at ~87 km throughout the years, except for the full moon period each month. In the meantime, as part of the international collaborative ANGWIN program, wintertime OH (3,1) temperature had been obtained by the USU Advanced Mesospheric Temperature mapper (AMTM) at the South Pole Station (90° S), starting in the winter season of 2010. These two unique datasets will be compared to investigate the mesospheric temperature variabilities at mid- and high latitudes for different time scales, as well as the long-term responses to solar influence.

## AS25-1167

# Tidal Amplification in the Lower Thermosphere during the 2003 October–November Solar Storms

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Using the National Center for Atmospheric Research's vertically extended version of the Whole Atmosphere Community Climate Model nudged with reanalyses, we examine the impact of the 2003 Halloween solar storms on atmospheric tides and planetary waves in the lower thermosphere (LT). One of the largest solar flares and fastest coronal mass ejections on record occurred on 30 October, resulting in significant energy transfer via Joule heating and auroral particle precipitation in the Earth's higher latitude thermosphere. In the simulation, that occurrence creates a large zonally asymmetric heating perturbation, amplifying the diurnal migrating tide (DW1), semidiurnal migrating tide (SW2), as well as non-migrating westward and eastward tides between 120–200 km. Large-amplitude bursts of DW1 in the Northern Hemisphere and non-migrating westward tides in the Southern Hemisphere lead to westward wave forcings, which strengthen the thermospheric wind. Planetary waves are also amplified, but their forcing is much weaker than the forcing exerted by tides in the LT. Non-migrating tides are generated by nonlinear interactions between tides, or between tides and quasi-stationary planetary waves, and *in situ* processes in the LT linked to Joule heating and auroral particle precipitation. The induced disruptions of the thermospheric mean meridional circulation reinforce the Spring thermospheric branch in the Southern Hemisphere at high latitudes and oppose the Fall branch in the Northern Hemisphere. Our examination could be relevant to understand the dynamical impact of recent geomagnetic storms that occurred in May 2024 and October 2024

## AS25-1267

# Varying centennial relation between sunspots and solar EUV irradiance: Implications to ionospheric driving and solar stellar evolution

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Several recent studies have examined which solar EUV proxies more closely drive the long-term evolution of ionospheric parameters like foF2 and foE. It has been found that the relation between ionospheric parameters and some solar proxies, like sunspots and F10.7, is not long-term stable but changes between the last 5–6 decades. On the other hand, the relation of ionospheric parameters and the F30 radio flux has been shown to be more stable over this time interval. These changes reflect corresponding multi-decadal changes in the mutual relation between solar proxies originating from different altitudes of solar atmosphere. Accordingly, fundamental long-term changes took place in the Sun since 1960s, during the time when the Modern Maximum, the latest Gleissberg cycle of high solar activity was decaying.

Here we use geomagnetic measurements at several long-running stations to extract a centennial proxy of solar EUV irradiance and to study its relation with sunspots over the whole Modern Maximum. We find that sunspot activity was larger in relation to EUV irradiance when solar activity increased in the early 20$^{th}$ century during the growth of the Modern Maximum, but EUV irradiance dominated over sunspots during the decay of the MM from 1960s onward. This proves that the changes between the many solar proxies during the last 50–60 years are indeed related to the large change of solar activity over the Modern Maximum.

We discuss the implications of these results to solar ionospheric driving, the long-term evolution of ionosphere and to solar stellar evolution.

## AS25-1355

# Tidal analysis of the new ExB vertical drifts unattended measurements over Jicamarca

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We present the first tidal analysis of the equatorial ExB vertical drifts measurements over the Jicamarca Radio Observatory (JRO), a facility of Instituto Geofísico del Perú (IGP). This work was possible due to the new JULIA-Medium Power mode that has allowed estimating ExB drifts almost continuously since its implementation. Our study analyses more than two years of data during high solar flux conditions (January 2023-present) and shows evidence of 24-h (diurnal), 12-h (semidiurnal), 8-h and 6-h tides, where the diurnal tide is the dominant component throughout the entire period of study and reaches its maximum of 28 m/s around the equinoxes, while during solstices the amplitude decreases to 18 m/s but it is still greater than the amplitudes of the other tides. The semidiurnal tide reaches its maximum of 17 m/s in January and decreases for the following months, and reaches its minimum in July where there is no contribution from this component (zero amplitude) to the total vertical drifts. An 8-hour tidal component has also been observed with maximum amplitudes of 12 m/s during the equinoxes and no contribution during the solstices. Moreover, predicted vertical drifts from the Scherliess-Fejer model have also been analyzed, where the estimated tides show the same seasonal variation for the different tides but with smaller amplitudes. This work is the first step in the attempt to determine which tides of the ground based vertical drifts measurements over Jicamarca are related to the ionosphere-atmosphere coupling and which ones are entirely due to the F-region dynamo.

## AS25-1475

# Responses of Planetary-Scale Waves to Sudden Stratospheric Warming Events: Insights from Multi-Year Meteor Radar Observations Across Multiple Longitudes at Mid-Latitudes

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Sudden Stratospheric Warming (SSW) events are frequently associated with the amplification of a wide range of planetary-scale waves, including migrating and non-migrating solar tides, higher-order solar tides, the lunar semidiurnal tide, planetary wave normal modes, non-normal modes, and secondary waves resulting from nonlinear interactions. However, substantial inconsistencies persist across previous studies, largely due to the reliance on single-satellite or single-station spectral analyses, which are inherently prone to aliasing effects. To address these limitations, we employed multi-year meteor radar wind observations from multiple longitudinal sectors over East Asia and Europe, and developed a suite of multi-station analytical techniques. Our results reveal several novel findings. First, many wave components near the 12-hour period—previously thought to amplify during SSWs—do not exhibit statistically significant enhancement, suggesting that earlier conclusions may have been influenced by neighboring-period wave interference. Second, the reported amplification of higher-order solar tidal harmonics (e.g., 8- and 6-hour tides) appears to be a misinterpretation of seasonal variability rather than a direct SSW response. Third, planetary wave behavior during SSWs is found to be significantly simpler than previously assumed: the observed waves are primarily low-wavenumber normal modes, with non-normal modes being rare. Finally, secondary waves generated through nonlinear interactions are shown to be far more diverse than earlier studies have indicated. These findings underscore the importance of multi-station observational approaches in achieving a more accurate and comprehensive understanding of mesospheric wave dynamics during SSW events.

## A14 Advances in Mid-Latitude, Low-Latitude and Equatorial Aeronomy

### AS25-0014

# Dynamic coupling of polar and equatorial ionospheric irregularities during the October 10–13, 2024 superstorm

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In this work, we analyze the atypical ionospheric irregularity patterns observed during the geomagnetic storm of October 10–13, 2024. This analysis is based on high-resolution Rate of Total Electron Content Index (ROTI) maps derived from data collected by approximately 1,600 Global Navigation Satellite System (GNSS) stations distributed across the American continent and Antarctica, complemented by local ionospheric observations. The morphological characteristics of equatorial and polar ionospheric irregularities during this extreme event are investigated. Our findings reveal a reversed-C-shaped depletion band extending from the magnetic equator to auroral latitudes, driven by the intensification of both vertical drift velocities at the equator and zonal drift velocities near the auroral region. Thus, the polar irregularity region expanded to midlatitudes, converging with stretched Equatorial Plasma Bubble (EPB) structures near ~45° MLAT, highlighting a dynamic coupling mechanism between these regions. Additionally, distinct longitudinal asymmetries in EPB behavior were observed, as they extended into midlatitudes and tied up with the polar irregularities along the western coast of South America (~0° MLON) but remained confined to the equatorial region along the eastern coast (~20° MLON). These asymmetries are attributed to variations in electric field penetration efficiency due to seasonally enhanced ionospheric conductivity. Finally, disturbance dynamo electric fields sustained F-region height, leading to an atypical occurrence of post-sunrise EPBs.

## AS25-0030

# Ionospheric Disturbances During a Geomagnetic Superstorm

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In May 2024, a geomagnetic superstorm occurred, with the Dst and Kp indices reaching -412 nT and 9, respectively. The storm sudden commencement (SSC) was recorded on May 10 at 17:05 UT, followed by the main phase from 18:00 UT on May 10 to 03:00 UT on May 11, while the recovery phase extended over several days. The storm induced significant ionospheric electrodynamic disturbances, driven by the occurrence of prompt penetration electric fields (PPEF), atypical equatorial spread F (ESF), F-layer stratification, traveling ionospheric disturbances (TIDs), and variations in the O/N2 ratio. Observations from ionosonde, GPS-TEC, and magnetometer networks enabled a comprehensive analysis of the ionospheric responses. The most intense disturbances included an extreme uplift of the F-layer, exceeding 1024 km in altitude, and pronounced F-layer stratification and ESF. Additionally, a strong negative ionospheric storm effect was observed during the daytime recovery phase on May 11, likely attributed to compositional changes in the O/N2 ratio. These findings provide critical insights into the electrodynamic and thermospheric processes that govern ionospheric responses during extreme geomagnetic events.

## AS25-0033

# Recent observations of the ionospheric meso-scale structures associated with equatorial ionization anomaly

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The equatorial ionization anomaly (EIA) is a well-known phenomenon of the low-latitude ionosphere during daytime, which is driven by the equatorial plasma fountain effect. EIA is typically a daytime phenomenon, characterized by a plasma density trough above the magnetic equator and double crests of enhanced plasma at about 15° north and south of the magnetic equator. Observations from recent satellite missions, like ESA's Swarm, NASA' GOLD and ICON satellites, reveal that in addition to the typical EIA two crests, meso-scale structures associated with EIA have frequently been observed, e.g., the third-peak at the poleward of EIA crest, the night-side latitudinal four-peak structure, or the X-pattern of EIA. In this report, we provide an overview of these meso-scale ionospheric structures, and their possible driven mechanisms have been discussed. These results indicate that though the ionosphere have been investigated for a hundred years, there are still unknown structures of ionosphere at the low and middle latitudes, due to the dynamic complicated processes.

## AS25-0036

# Occurrence of Ionospheric Irregularities Over the American and African Sectors During the SSW2019 Event Under Low Solar Activity

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A major Sudden Stratospheric Warming (SSW) event during the 2018–2019 Arctic winter impacted the dynamics of the equatorial and low-latitude neutral atmosphere, leading to disturbances in ionospheric electrodynamics and changes in the characteristics of ionospheric irregularities. Using bottom-side virtual height (h′F) measurements from the Araguatins (ARA) ionosonde station (dip latitude 4.2° S, near the Brazilian equatorial region), we observed pronounced day-to-day variations between 19:00 and 22:00 LT, closely associated with fluctuations in the post-sunset electric field's pre-reversal enhancement (PRE). During the SSW event, h′F values during the PRE were consistently lower and delayed compared to periods before and after the event. Additionally, the duration of equatorial spread F (ESF) events was reduced, suggesting that changes in h′F play a critical role in modulating ESF behavior. To further investigate ionospheric irregularities, we conducted a comparative analysis between ionosonde ESF observations at ARA and the rate of change of TEC (ROT) at the IMP station, located 80 km from ARA. Results revealed that irregularities detected via ROT had a shorter duration than those identified in ESF data. Furthermore, using four GPS-TEC latitudinal networks (two in the American sector and two in the African sector), we examined the meridional distribution of ionospheric irregularities. Our findings indicate that these irregularities are most prevalent in equatorial and near-equatorial regions, with their occurrence frequency decreasing at higher latitudes. Notably, the amplitude of GPS-derived ROT measurements was also reduced during the SSW event, highlighting the broader impact of SSW2019 on ionospheric electrodynamics.

## AS25-0037

# Recent expansion of mid and low latitude thermospheric wind observations

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Recently, new Fabry Perot interferometers (FPIs) for thermospheric wind observation have been deployed in mid- and low-latitude regions in the America and Africa sectors. The new observations reveal new features in the thermospheric dynamics in the mid and low latitude region. One new FPI was deployed at Athabasca, Canada. The instrument is in the sub-auroral region with frequent occurrence of SAPS, which motivated the deployment. Observations from Athabasca showed strong thermospheric winds response to minor magnetic activities, which were not previously observed nor shown in model simulations. Further study is planned. Another FPI was deployed in Korhogo, Cote d'Iovire. The new instrument opens a new window to explore low latitude thermosphere dynamics and space weather in the West Africa region. The observations show significant discrepancy with widely used thermosphere and ionosphere models. In this report we will show somenew results from these FPIs and discuss some future uses for these new observations.

## AS25-0049

# Medium scale ionospheric irregularities over a full solar cycle derived from global GNSS observations

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Ionospheric irregularities, which represent an ubiquitous spatial-temporal variation in the ionosphere, pose significant challenges to reliable radiowave propagation. Medium-scale ionospheric irregularities, particularly, medium-scale traveling ionospheric disturbances (MSTIDs), can intensify during enhanced geomagnetic and other geologic conditions. While characterizing these irregularities systematically across different regions (latitudes and longitudes) and time frames (seasons and solar cycles) remains a challenging task, the GNSS observations processed by the MIT TEC system since 2000 offer an unprecedented opportunity to study these irregularities comprehensively. In this study, medium scale irregularities are defined as the fluctuation component in TEC data (i.e., dTEC) with smooth and gradual background variations being removed using a 30-minute sliding window. We examine the intensity of dTEC variability over 2012–2023 with a focus on American longitudes (~70 W longitudes). Our results over the ~70 W longitudes reveal that the irregularities intensity maximizes at the equator, being stronger from September to December and March than from April through August, consistent with EPB seasonal variations in this longitude sector. At midlatitudes, the daytime intensity is larger in both winter and summer, whereas the nighttime intensity is larger in summer. Additionally, the irregularity intensity tends to be enhanced toward higher solar activity. These findings align with MSTID climatology at midlatitudes.

## AS25-0063

# Autonomous Detection of Large-Scale Travelling Ionospheric Disturbances via GNSS Data and Image Processing Methods

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Large-scale travelling ionospheric disturbances (LSTIDs) are irregularities affecting the ionosphere from auroral to low latitudes, with significant implications for radar systems and satellite navigation. To address the need for rapid detection and forecasting, we present an autonomous detection method based on travel-time diagrams of detrended Total Electron Content (TEC) data over the European region.

Our approach utilizes a network of GNSS dual-frequency receivers, selected through a K-Means clustering algorithm to optimize spatial coverage. By detrending the geometry-free linear combination of phase measurements, we generate daily travel-time diagrams that capture the meridional propagation of LSTIDs. We then apply image processing techniques to highlight regions of interest and extract propagating features with both positive and negative amplitudes. These features are fitted using the random sample consensus (RANSAC) method to estimate latitudinal velocities.

Analysis of data spanning 2021–2024 shows that typical LSTIDs in the European sector travel at a speed of 644 ± 211 m/s and have a period of 61 ± 11 minutes. Moreover, correlations with auroral electrojet and geomagnetic indices reveal that increases in auroral currents lead to faster, more pronounced, and shorter-period disturbances, in line with previous studies.

This work validates our detection methodology and establishes a foundation for future machine learning-based forecasting experiments of ionospheric disturbances.

## AS25-0090

# Statistical connections between MSTIDs and spread-F in summer nights over China middle latitude

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In this study, the connections between medium-scale traveling ionospheric disturbances (MSTIDs) and mid-latitude frequency spread F (FSF) during summer nights in the China sector are statistically investigated using data from over 250 GNSS stations and 12 ionosonde stations from 2014 to 2018. Firstly, both phenomena are observed to commonly occur on the same night during summer, with longer durations of FSF corresponding to higher average MSTIDs activity values. MSTIDs activity tends to precede the FSF occurrence. The statistical peak distribution of MSTIDs activity is concentrated before midnight, whereas FSF peaks after midnight, with median occurrence time differing by approximately 1–2 hours. Additionally, FSF and MSTIDs exhibit similar spatial propagation characteristics, with occurrences in the northeastern region occurring earlier in universal time (UT). Building on these findings, the potential physical processes and mechanisms by which MSTIDs may excite FSF were further discussed, including the role of E-F coupling, as well as significant changes in critical frequency and virtual height at different MSTIDs activity conditions. Furthermore, the underlying reasons for the differences in the temporal distribution of FSF at different latitudes were also analyzed. The midnight type FSF may be related to the disturbed electric fields in MSTIDs and gradient drift instability, while presunrise type FSF mainly concentrates at higher latitudes, without obvious connections to MSTID activity, suggesting the existence of excitation mechanisms beyond MSTIDs.

## AS25-0141

# Ionospheric response to geomagnetic storms of different intensity in the Eastern North Atlantic mid-latitudinal zone: comparison between Lisbon, Azores, Madeira

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Geomagnetic storms during the declining phase of the solar cycle 24 were studied using the total electron content (TEC) data obtained from three geodetic receivers located in Portugal: Lisbon (Continental Portugal), Furnas (Azores) and Funchal (Madeira). Two of the receivers (Lisbon and Furnas) are located at about the same latitude (~39ºN) while the third receiver (Funchal, ~33ºN) is positioned quite well to the south.

Previously, it was shown that for strong geomagnetic storms (Dst < -90 nT) TEC variations are synchronous along longitudes, but a latitudinal difference is regularly observed: at the most southern location the amplitude of TEC variations is often significantly higher than at other two.

In this work, we study TEC variations during all geomagnetic storms (Dst <= -50 nT) observed between 2015 and 2019. We draw conclusions on the strength and type of the ionospheric response, and on geomagnetic and other conditions that favour a significant ionospheric storm in the studied region. Also, we discuss the longitudinal and latitudinal (dis)similarities in the ionospheric variations.

## AS25-0180

# Empirical modelling of ionospheric changes due to CME and CIR driven storms using Feed Forward Neural Networks

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Results from empirical models of the ionospheric total electron content (TEC) changes due to coronal mass ejections (CMEs) driven storms on one hand, and co-rotating interaction regions (CIRs) driven storms on the other hand, will be presented and compared for low, northern and southern hemisphere mid-latitude locations. Derived TEC data from the Global Positioning System (GPS) measurements over Madrid (MAD2, Spain, 33.52° N geomagnetic), Mbarara (MBAR, Uganda, 10.22° S geomagnetic), and Hermanus (HNUS, South Africa, 42.34° S geomagnetic) will be used to train artificial neural network (ANN) based models, in conjunction with the standard modelling inputs that represent diurnal and seasonal variations of TEC, as well as solar and geomagnetic activities. Being aware of different mechanisms that drive CME and CIR driven storms, an assessment of local and global geomagnetic activity indices will be performed before the training process, to figure out which index is appropriate to each category of storms. Towards the improvement of the storm-time ionospheric models, the ionospheric cross polar cap potential being a good descriptive parameter of solar wind-Magnetosphere-Ionosphere coupling, will be introduced as new modelling input and a statistical analysis will be conducted to evaluate how much the added input contributes to the modelling results.

## AS25-0236

# Polar-type medium-scale traveling ionospheric disturbances in nocturnal 630-nm airglow images at subauroral latitudes

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Nighttime medium-scale traveling ionospheric disturbances (MSTIDs) are major ionospheric disturbances observed at various locations from high to low latitudes through radio sounding techniques, multi-point GNSS receivers, and airglow imagers. The 630-nm airglow imagers have an advantage to provide fine-scale two-dimensional images of nighttime MSTIDs and their temporal variations in high-time resolution of an order of minutes. In this presentation, we report a review of the "polar-type" MSTIDs based on observations of nocturnal 630-nm airglow images at subauroral latitudes. The polar-type MSTIDs observed at Tromsø (69.6° N, 19.2° E; magnetic latitude: 66.7° N), Norway, show characteristic (oscillatory) motion associated with auroral brightening occurring at latitudes higher than the MSTIDs (Shiokawa et al., JGR, 2012, https://doi.org/10.1029/2012JA017928; Yadav et al., JGR, 2020, https://doi.org/10.1029/2019JA027598). Recent results of airglow observations at Nyrölä (62.3° N, 25.5° E; magnetic latitude: 59.4° N), Finland, which is ~7 degree equatorward of Tromsoe, shows clear low-latitude boundary of polar-type MSTIDs (Sato et al., JGR, 2024, https://doi.org/10.1029/2023JA032077). These results suggest that the polar-type MSTIDs have specific generation mechanisms at subsuroral latitudes, probably driven by convection electric field at high latitudes.

## AS25-0259

# Climatological Assessment of Ionospheric Models Using Swarm Satellite In-Situ Electron Density Measurements

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The Swarm satellite constellation provides in-situ plasma density measurements in the topside ionosphere, offering a benchmark for ionospheric model validation. This study assesses the climatological performance of three models—International Reference Ionosphere (IRI), NeQuick, and 3D-NN (a neural network-based model trained on COSMIC radio occultation data)—by comparing their global electron density predictions with Swarm measurements from 2014, 2016, 2019, and 2022, covering different solar activity phases. Swarm data were binned in 15° longitude intervals, and quiet-time monthly latitudinal profiles were analyzed. Results indicate that all three models provide reasonable estimates but exhibit systematic biases. The IRI model performed best at northern mid-latitudes but overestimated densities above 450 km, particularly in the southern mid- and high-latitudes. NeQuick was more accurate at night but overestimated densities at mid-latitudes and during winter solstices. 3D-NN consistently outperformed IRI and NeQuick, especially during daytime and high solar activity, but underestimated densities at low and mid-latitudes. Overall, 3D-NN provided the most reliable predictions, while NeQuick performed better than IRI at Swarm B's altitude, and IRI was slightly better than NeQuick at Swarm A and C altitudes. These findings highlight the potential of AI-driven approaches for improved ionospheric modeling and space weather applications.

## AS25-0282

# Investigation of Midlatitude Spherical Asymmetries Using Modified Hausdorff Distances

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This study aims to investigate the spatial relationships between total electron content (TEC) trend structures across midlatitude regions, considering both hemispheres and varying solar activity levels. A total of 48 regions are taken into account; 24 in the northern hemisphere and 24 in the southern hemisphere. Each region covers 10 degrees in latitude and 20 degrees in longitude. For each region, hourly-monthly TEC trends are extracted, capturing seasonal and diurnal variations influenced by solar activity. Previous studies have shown that the TEC trend in the midlatitude can be represented by means of a locally planar model with only three coefficients: the mean and the slopes with respect to normalized latitude and longitude. To quantify spatial coherence between neighboring regions, Modified Hausdorff Distances are calculated between the planar trend model coefficient sets of each region and its immediate neighbors to the north (or south), east, west, northeast, and northwest (or southeast and southwest) grouped into hourly-monthly medians. This approach allows for a systematic evaluation of directional symmetries and asymmetries in TEC behavior across midlatitude regions. The results reveal, for the first time in the literature, quantifiable measures of north-south and east-west symmetry (or asymmetry) in the spatio-temporal evolution of TEC trends. These findings provide new insights into the spatial organization of ionospheric processes, with potential implications for regional ionospheric modeling and space weather monitoring at midlatitudes.

## AS25-0284

# IONOLAB-SMAP: A Method for Near-Real Time Ionospheric STEC Mapping

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The ionosphere profoundly affects the positioning accuracy of Global Navigation Satellite System (GNSS) receivers. In scenarios requiring high precision, it is crucial to anticipate these errors in advance, necessitating the modeling of ionospheric behavior. Current research frequently employs Total Electron Content (TEC) as a metric for assessing ionospheric fluctuations, with Global Ionosphere Maps (GIM) being widely adopted. However, GIMs exhibit limitations in temporal and spatial resolution, rendering them unsuitable for real time monitoring. This study aims to use the estimated Slant TEC (STEC) values from dual-frequency GNSS receiver measurements formatted in RINEX, utilizing the IONOLAB-STEC algorithm. It conveys these values using a new gridding technique based on the Kriging approach. The IONOLAB-SMAP algorithm, that has been developed in this study, facilitates near-real time interpolation, yielding high-precision maps with a temporal resolution of five minutes and a spatial resolution of 0.48 degrees both in latitude and longitude. The resulting maps for Turkey and Europe are contrasted with traditional mapping methodologies, revealing that Kriging-based STEC mapping provides superior spatial and temporal resolution compared to conventional TEC mapping techniques. This study represents a significant advancement, offering a more precise and timely approach to monitoring and predicting ionospheric conditions, crucial for applications requiring high-accuracy GNSS positioning and navigation.

## AS25-0295

# Uncertainties in the estimation of bottom-side ionospheric TEC in the IRI model over the low latitudes

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It is known that the ionospheric Total Electron Content (TEC) variations estimated by the IRI model show larger deviations from observed values over the low latitudes. While studies on the topside ionospheric contributions to the errors in the modelled TEC are under active consideration with different models of topside and altitude profiles, there have been no studies on the role of bottom-side ionospheric contribution to the TEC errors in the model vis-à-vis those observed. As ionosondes provide the ground truth of the bottom-side TEC, in this work, we have made a comparative study in discerning the role of various parameters that go into the estimates of bottom-side density profiles and electron content in the IRI model (TECb_iri). The digisonde observations over an EIA crest location, Ahmedabad, India are used to estimate the bottom-side electron content (TECb_digi) during 2015 and 2018. It is found that the TECb_iri is overestimated during day time irrespective of the season and solar activity, wherein, the maximum deviations with TECb_digi are noted during equinoctial months and high solar activity period. Among the F-layer peak and profile parameters, the model deviations in the bottom-side thickness (B0) are found to be consistent with the uncertainties in the TECb_iri. The agreements and discrepancies between TECb_iri and TECb_digi, under the influence of vibrant electrodynamic processes and solar flux will be discussed. This study provides crucial information required to delineate the contributions of different empirical parameters to address the discrepancies that exist in the bottom-side ionospheric modelling over the low latitudes.

## AS25-0351

# Ionospheric observations and modeling results during the 23–25 March 2023 geomagnetic storm over the African-European sector

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The 23–24 March, 2023 geomagnetic storm is known to have been associated with slowing down of the progression of the main phase by about 3 hours as a consequence of the sudden decrease in solar wind dynamic pressure resulting into modification of equatorial and low latitude electrodynamics through magnetosphere-ionosphere coupling. We present results of ionospheric changes during this geomagnetic storm using observational and modeling data over the African-European sector. Our ionosonde and Swarm observational results show that mid latitudes were characterized by negative storm effects which have been partly attributed to thermospheric composition changes. We investigate the capability of the models in reproducing the long-lived negative storm effect during the main and recovery phases over mid-latitudes in northern and southern hemispheres. Considered models were Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) and the three-dimensional storm time empirical model (3D-NNstorm) constructed based on radio occultation and ionosonde data. In terms of correlation coefficient values, TIE-GCM and 3D-NNstorm models' performance in estimating maximum electron density of the F2 layer ranged between 0.48–0.64 and 0.64–0.88, respectively, with lower performance observed at low latitudes for both models. In response to the sudden drop in solar wind dynamic pressure that occurred during the storm main-phase, we show that the low-latitude ionosphere experienced a decrease in total electron content which may have been due to the reversal of electric field from eastward to westward.

## AS25-0401

# Two-phase stormtime response of ionospheric electron temperature overshoot uncovered by neural networks

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An intense surge in equatorial electron temperature ($T_e$) at sunrise, known as the morning $T_e$ overshoot, has been one of the most widely studied ionospheric features since its discovery in the early Space Age. Despite extensive research, its behavior during geomagnetic storms remains poorly understood. Using global electron temperature observations by the CHAllenging Minisatellite Payload (CHAMP) mission in 2002–2010, we develop a global neural network Te model that can be considered a digital twin of the global $T_e$ distribution due to its excellent performance on independent data. The model revealed an unexpected two-phase stormtime response of the morning $T_e$ overshoot. During the storm's main phase, electron temperatures in the overshoot region exhibit a pronounced enhancement, followed by a dramatic depletion exceeding 1000 K and disappearance of the overshoot during the recovery phase. This evolution corresponds to the initial influence of a westward prompt penetration electric field (PPEF), which reduces electron densities, allowing for more efficient energy exchange between newly ionized sunrise particles and the lower-energy (depleted) ambient plasma. Later in the storm, the eastward disturbance dynamo field flips the **E**x**B** drift from downward to upward and lifts more electrons into the F-region. The resulting increase in electron density enhances cooling rates, leading to the overshoot's disappearance in the recovery phase. Our findings shed new light on the dynamics of the morning electron temperature overshoot and highlight the capability of digital twin models of the near-Earth space environment to uncover previously unrecognized physical patterns even for the most commonly studied phenomena.

## AS25-0406

# Impact of sudden stratospheric warming on sporadic-E layers: A multi-regional analysis

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This study examines the influence of Sudden Stratospheric Warming (SSW) events on sporadic-E (Es) layer behavior at low and mid-latitudes. Two independent analyses were conducted to assess the impact of SSW events in both hemispheres using ionosonde and meteor radar data. The first analysis investigated Es layer variations in the Brazilian sector during major SSW events (February 2018, December 2018–January 2019, and December 2020–January 2021). Data from ionosondes in Araguatins (ARA) and São José dos Campos (SJC) revealed frequency peaks reaching 20 MHz (~$5 \times 10^6$ electrons/cm$^3$) at both locations. Large values of ftEs, fbEs, and electron densities were observed at altitudes between 100 and 115 km, particularly in ARA. Wavelet analysis showed a 2-day periodicity in ftEs and fbEs at ARA before and after the central SSW day, while SJC exhibited similar patterns mostly after the event. The second analysis focused on the rare 2019 Antarctic SSW event, using ionosonde data from the American, Oceanian, and Asian regions. Observed ftEs peaks exceeded 10 MHz, with values reaching 20 MHz near the magnetic equator. Wavelet analysis indicated strong planetary wave (PW) and tidal interactions, generating 2–8-day oscillations in Es layers globally. These oscillations were linked to zonal and meridional wind variations, demonstrating stratosphere-thermosphere coupling. These findings highlight the role of SSW events in modifying Es layers via non-linear PW-tide interactions, contributing to improved ionospheric prediction models.

## AS25-0452

# Vertical drift velocity of equatorial plasma bubbles using the very high frequency (VHF) radar and ionosonde system

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Equatorial plasma bubbles (EPBs) [1] are depleted plasma density area originating at the bottom side of the ionosphere near the magnetic equator. Vertical drift velocity is an important factor during the initial stages of these bubbles as well as their growth. In this work, we analyze the vertical drift velocity of EPBs in 2020 from the recently installed VHF radar [2] and FMCW ionograms at Chumphon station, Thailand (Geographic: 10.72° N, 99.73° E, Geomagnetic: 1.33° N), situated near the magnetic equator. VHF radar data are used to calculate the vertical drift velocity at every 15 minutes, which is calculated as the altitudes of the bottom side of the EPB formed on the QL plot image by using the Fd3 (Overhead beam). For the ionosonde, it is also calculated from the ionograms at every 15 minutes based on the h'F parameter. For example, the vertical drift velocity of the EPBs from VHF radar data and ionograms are 20 to 25 meters per second. VHF radar can detect plasma bubbles up to an altitude of 800 kilometers, which is an advantage over ionosonde since the ionosonde could not capture the traces of EPBs beyond 400 km. In addition, we investigate other EPB characteristics such as the latitudinal and longitudinal widths.

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## AS25-0508

# Simultaneous unusual occurrence of three non-interacting mid-latitude ionospheric plasma structures over Himalayan region

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An unusual event of three characteristically different plasma structures on a geomagnetically quiet night (Ap = 4) of 08 July 2018 has been investigated in this paper using an all-sky imager installed at Hanle, Ladakh (32.7° N, 78.9° E; Mlat. ~24.1° N), India. These structures include a freshly generated electrified medium scale traveling ionospheric disturbances (EMSTID), ambiguous plasma depletions, and a northward propagating non-electrified MSTID. One of the most fascinating aspects of this event was the lack of mutual interaction between the three structures, even though they existed simultaneously and propagated in different directions. They individually underwent evolution, distortion, and dissipation separately. One of the structures was an EMSTID, which got generated within the imager's field-of-view (FOV) and evolved with time. As time progressed, different strip-like structures travelled southwestward, merged with each other to form the EMSTID. The second structure was plasma depletions which appeared in the southeastern part of the FOV. They eventually merged into a single band, which propagated nearly westward. The merged band evolved with time, extended further northward, and dissipated later. Along with these, a very rare non-electrified MSTID structure with east-west aligned fronts was observed which propagated northward. Its fronts underwent distortion, became curved, and dissipated. In this study, we have explored the role of electrodynamics behind the observed unique features of the three plasma structures. The details of the results will be discussed in the meeting.

## AS25-0639

# Investigation of Ionospheric response to the May 2024 Super Storm over Egypt based on GNSS observations

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The May 2024 geomagnetic storm, driven by intense solar activity from Active Region AR 13664, ranks among the most significant space weather events in recent history, with a minimum Dst index of −412 nT. This study offers a comprehensive investigation into the ionospheric response over Egypt, a region strategically located near the northern crest of the Equatorial Ionization Anomaly (EIA), encompassing both mid-latitude and low-latitude aeronomy during such geomagnetic disturbances. Utilizing vertical total electron content (VTEC) data from 27 GNSS stations across Egypt, we analyzed the storm's impact on ionospheric dynamics, including VTEC variations and the detection of traveling ionospheric disturbances (TIDs). Solar observations from GOES-16 and SDO/HMI provided insights into the evolution of AR 13664, which produced 12 X-class solar flares and multiple coronal mass ejections (CMEs). GNSS-derived VTEC data were compared with predictions from the International Reference Ionosphere (IRI-2020) model to assess deviations during the storm. Geomagnetic indices, including the interplanetary magnetic field (Bz), solar wind speed (SWS), and Dst index, were analyzed to characterize the storm's phases and their effects on Earth's magnetosphere. Key findings reveal significant VTEC depletion during the storm's main phase and strong enhancement during the recovery phase compared to the monthly average VTEC for May 2024 (VTECmm). Additionally, poleward-propagating TIDs were identified, highlighting their impact on radio communication and navigation systems. This study underscores the importance of advanced modeling and real-time monitoring to enhance space weather forecasting and mitigate the risks posed by extreme geomagnetic activity in regions like Egypt.

## AS25-0706

# U-Net Based Model on Image Denoising for Spread-F Types Classification in FMCW-Type Ionograms

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An ionogram image provides essential data for analyzing the characteristics and variations of the ionospheric bottomside. However, diffused echoes in these images create challenges for accurate interpretation, particularly in ionograms from the FMCW ionosonde system. This study presents an automatic classification of Equatorial Spread-F (ESF) using a U-shaped Network (U-Net) as an image preprocessing method. U-Net, a deep learning architecture designed for image restoration and segmentation, denoises ionogram images before training with the Visual Geometry Group (VGG) based model on the Convolutional Neural Network (CNN) [1]. A U-Net structure, with its encoder-decoder design and skip connections, preserves spatial information while refining image details, improving ionogram quality by reducing noise. This approach results in feature extraction enhancement and classification performance.

As the results, the classification model successfully classified Clear, Frequency Spread-F (FSF), Range Spread-F (RSF), Strong Spread-F (SSF), and Unidentified classes. By using U-Net for denoising, the overall classification accuracy reached 95.0%, outperforming previous work using ImageDataGenerator, which achieved 92.9% accuracy [1]. When combining both methods, the model accuracy increased further to 95.5%. The analysis shows that high-quality, noise-reduced ionogram images enhance the model ability to distinguish Spread-F types. A larger, more diverse dataset, also increase classification performance. These findings underscore the effectiveness of preprocessing in ionogram classification, demonstrating how high-quality imaging improves machine learning classification models in ionospheric analysis.

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## AS25-0780

# Statistical models of night-time equatorial F region plasma irregularities based on Swarm geomagnetic and electron density data

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Post-sunset equatorial F-region plasma irregularities characterize the night-time low latitude ionosphere. They pose a significant threat to the accurate positioning and timing of satellite navigation systems, such as the Global Positioning System (GPS), by disturbing trans-ionospheric radio wave signals.

While it remains an ongoing challenge to forecast irregularity events on a day-to-day basis, their climatological distribution can be well described through long-term and globally distributed satellite observations.

Recently, the IBP model, a statistical model based on 11 years of Swarm and 9 years of CHAMP magnetic data, has been developed to predict the low-latitude ionospheric irregularities and is publicly available (Stolle et al., 2024). The model is part of ESA's Swarm product portfolio. It provides an occurrence probability of the F region irregularities for a given local time, solar radio flux, day of year, and longitude. The model is capable to effectively estimate the monthly occurrence rates of Global Positioning System (GPS) scintillations. However, the IBP model has difficulty detecting low amplitude plasma depletions, which are often related to equatorial F-region plasma irregularities after local midnight. This is because they do not produce a detectable magnetic signal.

This study presents the results of a new model development based on 11 years of electron density data collected by Swarm, and a comparison is made with respect to the IBP model derived from magnetic data.

### Reference

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## AS25-0798

# Unusual variation in Nitric Oxide radiative flux and neutral density over Hunga-Tonga region caused by the volcanic eruption

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Large-scale volcanic eruptions, such as the Hunga-Tonga volcanic eruption that occurred in 2022, can impact the atmospheric structure and dynamics in a highly complex way. The response of Nitric oxide (NO) radiative emissions to the lower atmospheric forcing caused by the Hunga-Tonga eruption has been examined in this study using SABER measurements. On 15 January, neutral densities and NOIRF (Nitric Oxide Infrared Radiative Flux) were found to be depleted over the Hunga-Tonga following the volcanic eruption, as observed by Swarm and SABER. Subsequently, the following day, a significant and highly localized enhancement in NOIRF is observed. Using TIEGCM (Thermosphere Ionosphere Electrodynamics General Circulation Model) simulations with gravity wave input, it has been established that wave-induced lower atmospheric forcing is primarily responsible for the compositional and temperature changes. These changes influence the vibrational excitation mechanism of NO, resulting in the observed emission pattern during the Hunga-Tonga event.

## AS25-0818

# Near-Earth Objects: A Study Using Optical and Radio Systems

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The majority knowledge about physical characteristics of Near-Earth Objects (NEOs) comes from studying those that enter the Earth's atmosphere, and there is a significant danger from the class of objects that produce strong blast/shock waves during their terminal flight stage. We think that the presented data on Near-Earth Objects (NEOs) are quite unique for their completeness. They include GNSS network system to determination of the hydrodynamic energy injected in the upper atmosphere, All-sky images to determine the trajectory and location, sodium/potassium Lidar measurement to estimate the altitude of the events. Also, we used a meteoric radar network (SkiYmet system) to estimate the winds in the mesosphere-lower thermosphere (MLT) region. Most of the NEOs events analyzed were fireball (14 events), 4 events were classified as space debris. However, 2 events were unidentified flying objects. The GNSS data analysis of the generation and propagation characteristics of infrasonic pressure waves excited during the NEOs entry into the Earth's upper atmosphere/ionosphere is presented. These results have implications for the use of infrasound measurements as a tool for evaluating the flux of NEOs. In this work, we present and discuss several features related to the NEOs in the upper atmosphere/ionosphere.

## AS25-0849

# Multi-frequency Observations of Post-sunset Plasma Structures from an Anomaly Crest Station

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This paper reports multi frequency multi-instrument observation of post-sunset plasma structures through an Incoherent Scatter Radar system, Navigation with Indian Constellation (NavIC) and Global Positioning System from Kolkata,India; a station situated near the northern crest of the Equatorial Ionization Anomaly (EIA). Efforts have been made to study the dynamics of simultaneous detection of plasma structures over a wide range of frequency, starting from VHF through L-band and S-band. The data have been used from the Incoherent Scatter Radar, which is operational at 53 MHz at Ionosphere Field Station (IFS),(latitude: 22.93° N; longitude: 88.51° E geographic; magnetic dip 36.2° N) situated at 50 Km North-east of Kolkata, India. The received data of NaVIC ( ~ 2.5 GHz) and GPS (~1.6 GHz) have been taken from the Observatory of the University of Calcutta, Kolkata (latitude: 22.58° N, 88.38° E geographic; magnetic dip: 36° N). The spatial and temporal variations of plasma structures affecting different radio frequencies have been presented in this paper. Observations have been made during the equinoctial months of 2022–2023. It have been noted that the common impact zone located within 12°–28° N and 83°–89° E of the different radio frequency links spanning from 53 MHz to 2.5 GHz. During this coordinated observations, plasma structures have been observed by incoherent scatter radar with a signal- to-noise ratio (SNR) of 5–30 dB. At the same period of observation, intense (S4> = 0.6) L band scintillation was observed on multiple SVs and moderate (0.4<s4<0.6) to intense (s4> = 0.6) scintillations observed at S band signal.

## AS25-0953

# Unusually Strong Equatorial Ionization Anomaly Across Three Local Time Sectors During the Intense 10–11 May 2024 Geomagnetic Storm

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The Earth's upper atmosphere is significantly influenced by space weather events, particularly geomagnetic storms. In this study, we investigate the impact of an intense geomagnetic storm that occurred on 10–11 May 2024 (popularly known as Mother's Day storm) on the equatorial and low-latitude ionosphere. Using datasets from various ground and satellites-based (SWARM, and GOLD satellites, Global GNSS receivers, Incoherent Scatter Radar (ISR), Fabry- Perot interferometers (FPI), and magnetometer) measurements, we show the impact of extreme prompt penetration of electric field on the development of plasma fountain during the storm. Prompt penetration electric field caused a significant enhancement in the ionospheric vertical drift (~ 95 m/s) and the equatorial electrojet strength (~275 nT) over Jicamarca. These extreme eastward electric field perturbations, along with the large meridional wind, significantly altered the F-region plasma fountain at different local times. The afternoon equatorial ionization anomaly (EIA) not only sustained for an exceptionally long duration (~ 12 hr) but also expanded spatially over time. EIA crests extended beyond ±35° MLat in both hemispheres over the Jicamarca meridian during the afternoon and evening hours, eventually merging with the aurora. This study shows, for the first time, that unusually strong EIA can not only develop at different local times but can also sustain for long duration under favorable conditions, which has implications for space weather applications.

## AS25-0955

# Simultaneous observations of orthogonal nighttime MSTIDs at conjugate African-European midlatitude stations: 4 October 2018 case study

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This study reports on orthogonal nighttime medium-scale traveling ionospheric disturbances (MSTIDs) observed by conjugate midlatitude all-sky imagers in Sutherland (32.4ºS, 20.8ºE; magnetic latitude: -40.9º) and Asiago (45.87ºN, 11.53ºE; magnetic latitude: 40.3º) on the 4th of October 2018. These MSTIDs had fronts elongated along the northeast-southwest (NE-SW) and northwest-southeast (NW-SE) directions in the Southern and Northern Hemispheres, thus the orthogonal orientation. The NE-SW aligned MSTIDs propagated in the NW (SE) direction in the Southern (Northern) Hemisphere, while the NW-SE aligned MSTIDs propagated in the NE (SW) direction in the Southern (Northern) Hemisphere. This study reports the first optical observations of conjugate NE-SW/NW-SE aligned and equator-eastward propagating MSTIDs. These MSTIDs were observed in conjunction with gravity waves in the mesosphere that were detected by the Asiago imager and therefore could be linked to gravity wave-induced polarization electric field in the Northern Hemisphere that was mapped to the Southern Hemisphere. Their propagation direction was determined by background modeled and observed neutral winds, which favored the equator-eastward direction. The NE-SW/NW-SE aligned and equator-westward propagating MSTIDs were likely generated through the coupled Perkins and sporadic E instabilities, since they were observed in the presence of sporadic E layers and ideal Perkins instability growth rates. Polarization electric fields induced by the observed gravity waves and sporadic E layers provided positive mutual feedback that promoted the development of the conjugate and orthogonal MSTIDs.

## AS25-1122

# Daytime and Nighttime Variations of Electric and Magnetic Fields in the Equatorial Ionosphere During the Geomagnetic Storm of May 2024

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The equatorial ionosphere undergoes significant perturbations during geomagnetic storms due to various electrodynamic processes. At low magnetic latitudes, two primary mechanisms are thought to drive these perturbations: the penetration of high-latitude electric fields into lower latitudes and the ionospheric dynamo induced by storm-time thermospheric winds. In this study, we utilize ground-based magnetic records and vertical ion drift measurements to analyze the variations of electric and magnetic fields in the equatorial ionosphere during the major geomagnetic storm of May 2024. We present the results of simultaneous observations in two regions separated by approximately 12 hours in local time, allowing a comparative analysis of daytime and nighttime variations. Our findings demonstrate a strong correlation between electric and magnetic field perturbations, particularly during southward excursions of the IMF Bz. However, we also address instances where this correlation is weaker. Notably, perturbations in electric and magnetic fields are observed during nighttime, exhibiting a reversed polarity compared to daytime variations. Additionally, magnetic records separated by about two hours in local time help identify the potential effects of storm-time thermospheric winds on the ionospheric dynamo.

## AS25-1259

# Persistent Equatorial Plasma Bubbles During 2025-New Year's Geomagnetic Storm: First Insights from Multi-instrument Observations over East and Southeast Asian Longitudes

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The present study investigated the anomalous formation and evolution of Post-Sunset to Pre-Sunrise Equatorial Plasma bubbles (EPBs) during the recent 2025 New Year's Day geomagnetic storm over the East/Southeast Asian regions. Multi-instrument observations such as Amplitude Scintillation Index (S4) derived from the GNSS Ionospheric Scintillation and Total Electron Content Monitor (GISTM), GPS-derived Rate of change of TEC Index (ROTI), and Digisonde observations of foF2 and h'F to characterize the occurrence of EPBs. During the main phase of the storm, EPBs are initially formed in equatorial and low-latitude regions with moderate intensity and sustained for more than eight hours. After 1800 UT on January 01, coinciding with the storm recovery phase, the EPBs are intensified and extended to the mid-latitude regions. These EPBs then persisted for over four hours, which disappeared before sunrise. The prolonged development and persistence of these EPBs are attributed to the complex interaction of storm-induced Prompt Penetration Electric Fields (PPEFs) and the abrupt northward flipping of the Interplanetary Magnetic Field (IMF) Bz. Supplementary observations from other ground and satellite-based techniques are used to examine the latitudinal variability and the evolution process of Post-sunset to Pre-Sunrise EPBs. This research aims to develop strategies for mitigating the impact of severe space weather events on critical infrastructure, such as satellite communication and navigation systems over the equatorial and low latitude regions.

**Keywords**

Geomagnetic Storm, Equatorial Plasma Bubbles, Global Navigation Satellite System, Total Electron Content

## AS25-1266

# Impact of the equatorial ionosphere anomaly on the thermosphere interhemispheric circulation

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We investigate interhemispheric circulation at the solstices to understand why $O/N_2$ is larger in Northern Hemisphere winter than in Southern Hemisphere winter. Our studies reveal that the equatorial ionization anomaly (EIA) significantly influences summer-to-winter winds through plasma-neutral collisional heating, which modifies the summer-to-winter pressure gradient, and through ion drag. As a result, the wind is suppressed in the summer hemisphere when it encounters the EIA but accelerates after passing the EIA in the winter hemisphere. This wind then converges due to an opposing pressure gradient driven by Joule heating in auroral regions, leading to enhanced $O/N_2$ at subauroral latitudes. The EIA's influence is stronger near the December solstice than the June solstice because the ionospheric annual asymmetry drives greater meridional wind convergence in December. This, in turn, results in higher $O/N_2$ during Northern Hemisphere winter compared to Southern Hemisphere winter. The impact of the EIA on interhemispheric circulation may serve as a key mechanism through which sudden stratospheric warmings (SSWs) influence middle and high latitudes in the upper atmosphere.

## AS25-1343

# Evidence of Substorm-Driven Penetration Electric Fields Structuring the Nighttime Low-Latitude Ionosphere: Development of EPBs and Severe Scintillation

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This work presents evidence that even during mild geomagnetic activity (-27 nT ≤ SYM-H ≤ 6 nT), substorm-driven penetration electric fields can change the upward drifts, contributing to the development of Equatorial Plasma Bubbles (EPB). The EPBs, in turn, led to severe scintillation in L-band signals, which would otherwise have been absent, as observed on the nights surrounding the events. While previous research typically concentrates on events observed during very strong geomagnetic storms, we used an alternative approach to remove, as much as possible, contributions from interplanetary and Disturbance Dynamo effects, thereby enabling a more unambiguous evaluation of the contributions from substorm-driven penetration electric fields. We also carefully selected observations in which multiple short-lived substorms occurred under very consistent seasonal and solar flux conditions. We used a combination of ground-based and space-based observations, providing an ideal opportunity to assess: 1) how substorm-driven penetration electric fields influence electrodynamical processes at low latitudes during the early nighttime, and 2) their effectiveness in fostering the development of EPBs and severe scintillation in L-band signals. The results show that, even under mild geomagnetic activity, substorm-driven penetration electric fields – though subtle and short-lived – play a crucial role in driving upward drifts, facilitating the formation of EPBs, and enabling the occurrence of severe scintillation. Therefore, substorms occurring during the early nighttime are especially impactful, and their influences are expected to be most pronounced during late spring and early fall (in the northern hemisphere), when the prereversal vertical drifts are moderate.

## AS25-1382

# Mid-latitudinal topside ionosphere irregularities: relations with Spread-F

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As the high-cadence in-situ ionospheric topside plasma density measurements become available from multiple satellites, we analyse them to show relations with ground-based observations of ionospheric F-layer.

European Space Agency Swarm satellite triplet provides already 11 years of useful data, moreover the original Swarm Ionospheric Plasma Irregularities (IPIR) data products, originally using only 2 Hz Langmuir probes, were recently accompanied by similar product using Face plate detector (FP) instead. FP with 16 Hz plasma density sampling showed cascading effect of ionospheric topside plasma irregularities at high-latitudes.

The Formosat-5 Advanced Ionospheric Probe (AIP) provides kHz-rate measurements in Ion Density Mode at low- and mid-latitudes, but at high orbital altitude of 720 km. Nevertheless, there can be evaluated specific scales involved in irregularities observed at high kHz rates also by Norsat-1 satellite, at similar orbital altitudes like of the highest-flying Swarm-B (530 km). Norsat-1 data indicated ionospheric disturbances at meter-level scales at the high-latitudes. Plasma density data from COSMIC-2 and ICON, where 1 Hz data represents the scale sizes of ~7.5 km provide indications only at low-latitude ionosphere.

The ground-based multi-point Continuous Doppler Sounding (CDS) systems also at mid-latitudes often observe the indications of the F-region plasma irregularities known as Spread-F, common for the equatorial ionosphere. That brings opportunity to better understand this phenomena by comparing it to in-situ plasma irregularities occurring above it.

## AS25-1432

# Equinoctial Asymmetry in Solar Quiet Fields

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Equinoctial asymmetry of the amplitude of the solar quiet variation (SqH) of the horizontal geomagnetic field (H) has been found in some low latitude geomagnetic observatories for more than half a century. However, its global characteristics and physical mechanisms are still unclear. Using the hourly data of the horizontal (H) component of the geomagnetic field from more than one hundred geomagnetic observatories within the magnetic latitude range of 60° in both the northern and southern hemispheres of the globe since 1947, the global characteristics of the equinoctial asymmetry of the SqH amplitude were investigated. There was a significant latitude distribution in the observatories of the 120° E meridian chain. The signs of the equinoctial asymmetry of the SqH amplitude were opposite between the observatories located at the northern and southern sides of the Sq current focus. It showed larger values around spring than autumn equinox at southern observatories, but behaved opposite at northern observatories. The Result from linear fitting presented a positive dependence of the asymmetry coefficient on geographic latitude, with a reversal of the asymmetry occurring at 28.1° N near the focus of the average Sq current. Additionally, longitudinal differences and hemisphere asymmetry were also found by examining three meridian chains. By correlating with F10.7 index and the dipole field, non-dipole field, and internal field of the Earth calculated by the 13$^{th}$ International Geomagnetic Reference Field model, the result suggested that the non-dipole magnetic field might be closely related to the longitudinal difference of the equinoctial asymmetry of the SqH amplitude.

## A15 Energetic Particle Precipitation Impacts on the Ionosphere, Upper Atmosphere, and Climate System

### AS25-0171

# D-region energetic electron precipitation due to electromagnetic ion cyclotron (EMIC) waves: energies and electron densities using multi-instrument observations

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Earth's outer radiation belt electron population is highly dynamic, in part due to the interaction of electrons with a variety of electromagnetic waves. It has been proposed, for example, that electromagnetic ion cyclotron (EMIC) waves can cause the precipitation of energetic electrons into the lower ionospheric D-region. Here we present a novel combination of observations indicating D-region energetic electron precipitation due to EMIC waves. We identify EMIC waves using the Sodankylä Geophysical Observatory's (SGO) array of search coil magnetometers (SCM) and monitor the lower D-region using SGO's Very Low Frequency (VLF) receiver observations at Kilpisjärvi (KIL), Finland, of 16.4 kHz transmissions from the Noviken facility (call sign JXN) in Norway. Using the European Incoherent Scatter (EISCAT) UHF radar (Tromsø, Norway), we investigate how the electron density (*Ne*) profile changes when energetic electron precipitation occurs due to the EMIC waves. We focus on dayside magnetic local times across northern Scandinavia during a quiet interval in March 2023. In the SCM data, we see a clear train of EMIC waves at Abisko (Sweden) on the JXN-KIL VLF path, ~130 km from the UHF radar. During the seven-hour train of EMIC waves, the VLF receiver data simultaneously shows amplitude and phase perturbations consistent with precipitation. The EISCAT UHF shows layers of significantly elevated electron density *Ne* at ~66 km and ~83 km for several hours. Individual minute-by-minute EISCAT profiles also show *Ne* peaks around 55 km consistent with relativistic energy electron precipitation around ~1 MeV.

## AS25-0368

# Empirically determining cutoff latitudes for protons originating from Solar Proton Events

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Solar proton events deposit highly energetic protons into the high latitude polar regions, increasing ionization to altitudes as low as ~40 km and driving chemical changes over altitude ranges from ~40 km–100 km. The increased ionisation triggers Polar Cap Absorption events, making radio communications in the poles much more challenging—a particular issue for high-latitude navigation. In this study we have developed a method for determining the time-varying proton cutoff invariant latitudes from observations made by multiple POES satellites over the course of solar proton events. The magnetic local time, Kp, and Dst were recorded at the same times as the proton cutoff latitudes. The new method is tested against previous methods. We find that when the fluxes are high the cutoff latitudes are similar. However, the new method has less overall scatter at lower proton flux levels. In total, 22 solar proton events were selected to be analysed and once the noise floor was removed 11,060 proton cutoff latitudes were identified. Four magnetic local time sectors are considered, with dayside cutoffs showing significantly different behaviour to nighttime cutoffs. In order to explain the observed cutoff variations, empirical models describing dayside cutoff behaviour have been developed based on Dst, while nightside models are based on Kp. As such, these models provide a step forward in identifying the latitudinal limits of where and when solar protons impact the atmosphere.

## AS25-0443

# ELFIN data set of solar electron forcing: impact on polar atmospheric NOx and ozone

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The latest recommended solar forcing data sets include also solar energetic particles and galactic cosmic rays. These are used for atmospheric and climate simulations, including those of the Coupled Model Intercomparison Project (CMIP), to study the atmospheric response over daily-to-decadal time scales. Concerning the solar electron forcing, data from the Medium Energy Proton and Electron Detectors aboard the Polar Operational Environmental Satellites provide the longest time series of measurements available and good statistics for proxy models. These are utilised also in the solar forcing recommendation for CMIP Phase 7. On the other hand, new small-satellite missions such as Electron Losses and Fields Investigation (ELFIN) can provide data with finer energy resolution and an extended range at higher energies, but have much shorter time series of observations. In this paper, we make use of these new data sets and compare their atmospheric impact in Whole Atmosphere Community Climate Model simulations. In this preliminary comparison, we show that both the CMIP7 and ELFIN have increased electron fluxes compared to the previous CMIP6 recommendation, which enhances polar atmospheric NOx production and ozone response in simulations. Thus, these new data sets should make the overall atmospheric and climate response stronger and more comparable to the observations.

## AS25-0786

# Observing ULF-Modulated Electron Precipitation via Balloon-Borne Timepix Measurements During the May 2024 Superstorm

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Accurate monitoring of energetic electron precipitation (EEP) events requires high-fidelity measurement techniques. In this study, we present results from a novel low-cost, lightweight, and low-power radiation detector payload, utilizing a CMOS pixelated Timepix chip, designed for high-fidelity detection of EEP via bremsstrahlung X-rays, generated in the atmosphere. During the May 2024 superstorm, a student-led balloon flight from Edmonton, Alberta, successfully carried this payload to an altitude of 33 km, obtaining detailed measurements of storm-time electron precipitation.

The payload data captured a distinctive four-peak structure in X-ray flux, each peak lasting approximately two minutes, indicative of intense, periodic electron precipitation bursts. Ground-based riometer data recorded coherent absorption signatures coincident with these X-ray peaks, validating the balloon-based measurements. Concurrent observations from the equatorial Arase satellite showed modulated trapped electron fluxes and periodic enhancements of lower band chorus waves, aligning well with the balloon's precipitation events. These periodic structures are likely driven by electron loss modulation via a Pc5 ultra-low-frequency (ULF) wave observed simultaneously.

This flight demonstrates the capabilities and value of Timepix-based devices for space weather monitoring. Given their successful deployment on weather balloons, these detectors are promising candidates for broader use on various platforms, including high-pressure balloons, high-altitude aircraft, and spacecraft. We are planning future launches, potentially in coordination with Canada's upcoming RADICALS mission and related satellite campaigns, to advance our understanding of the processes driving intense electron precipitation and their broader space weather implications.

## AS25-0910

# Solar forcing for CMIP7

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Back in 2017, solar forcing recommendations for the 6th round of the Coupled Model Intercomparison Project (CMIP) were provided which covered, for the first time, all relevant solar irradiance and energetic particle contributions. Since then, this dataset has been extensively used in climate model experiments and has been tested in various intercomparison studies. Furthermore, new datasets have become available. An ISSI Working Group has been established to review these recent achievements in order to define the strategy for building a revised solar forcing dataset for the upcoming CMIP7. After receiving community feedback on this strategy, a historical solar forcing dataset for CMIP7 has been recently constructed. Major changes with respect to CMIP6 include the adoption of the new TSIS-1 solar reference spectrum for solar spectral irradiance and an improved description of top-of-the-atmosphere energetic electron fluxes, as well as their reconstruction back to 1850 by means of geomagnetic proxy data. Solar irradiance variability in the reference forcing dataset is based on historical reconstructions generated with a preliminary version of the new empirical NASA NOAA LASP Solar Spectral Irradiance Version 1 model, NNLSSI1. In adition, an alternative solar irradiance dataset, based on SATIRE, is provided for sensitivity experiments. In this talk we will discuss the applied modifications with respect to CMIP6 and their implication for climate modeling, based on a set of dedicated evaluation experiments, with a particular emphasis on energetic particle forcing. Ongoing activities on uncertainty quantification and the construction of future solar forcing scenarios will also be summarized.

## AS25-0946

# Ground based validation of the EPP models by the EISCAT incoherent scatter radar datasets

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The energetic particle precipitation (EPP) forcing is included into the recent CMIP climate modelling recommendations. According to these simulations, the impact of inclusion of the medium energy electrons to the ozone variability was estimated to be 12–24% in the mesosphere and 5–7% in the stratosphere. However, to obtain a continuous particle forcing required for these multi-decadal simulations, the precipitating particle flux spectrum was parameterised by the magnetic Ap index to match statistically to the POES satellite's MEPED particle detector data. This rather simple approach has several uncertainties, but the most critical one is that the existing satellite-borne particle detectors, including the MEPED instrument, struggle to separate the loss cone populations from trapped particles, leading to biases in EPP forcing especially in the relativistic energies. In this presentation, we evaluate the modelled electron densities against the EISCAT VHF datasets. This approach provides a direct ground-truth evaluation of the ionisation taking place in the mesosphere-lower thermosphere.

## AS25-1132

# Investigating Space Radiation and Atmospheric Climate Impacts with the Canadian RADICALS Mission

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The RADiation Impacts on Climate and Atmospheric Loss Satellite (RADICALS) mission, scheduled for launch in mid-2027, is a Canadian small satellite mission designed to investigate the impacts of energetic particle precipitation on Earth's atmosphere. Energetic particle precipitation (EPP) plays a critical role in altering atmospheric chemistry, particularly through the production of NOx and HOx, which catalytically destroy ozone in the middle atmosphere. RADICALS will focus on measuring the energy input from precipitating energetic particles into the atmosphere, shedding new light on the connection between space weather and climate. Operating in a polar orbit, the RADICALS payload contains dual High Energy Particle Telescope (HEPT) suites (each comprising high and low energy telescopes, and a high temporal resolution scintillator), and dual X-Ray Imager (XRI) suites. When mounted on the spinning RADICALS spacecraft they will provide pitch angle distributions of trapped radiation belt electrons and solar energetic protons, and the associated Bremsstrahlung X-rays from atmospheric interactions. The mission's unique back-to-back HEPT suite design will measure both down-going and up-going particles simultaneously, while the XRI will remotely sense particle precipitation via X-ray emissions as well as monitoring lower energy electrons as a secondary product. The payload also includes a pair of boom-mounted fluxgate magnetometers and a 3-axis and search coil magnetometer to substantiate particle measurements with the local magnetic wave activity. By resolving the electron loss cone and quantifying the energy flux of precipitating particles, RADICALS will provide essential data for understanding how space radiation influences atmospheric chemistry, particularly during geomagnetic storms.

## AS25-1169

# Energetic particle precipitation influences global secondary ozone distribution

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The secondary ozone layer is a global peak in ozone abundance in the upper mesosphere-lower thermosphere (UMLT) around 90–95 km. The effect of energetic particle precipitation (EPP) from geomagnetic processes on this UMLT ozone remains largely unexplored. In this research we investigated how the secondary ozone responds to EPP using satellite observations. In addition, the residual Mean Meridional Circulation (MMC) derived from model simulations and the [O], [H], temperature measurements from satellite observations were used to characterise the residual circulation changes during EPP events. We report regions of secondary ozone enhancement or deficit across low, mid and high latitudes as a result of global circulation and transport changes induced by EPP. The results are supported by a sensitivity test using an empirical model. The relevant ozone signatures during for the recent solar storms of May and October 2024 are briefly discussed.

## AS25-1194

# Wintertime transport of polar mesospheric NOx in 21st century WACCM-D simulations

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The transport of mesospheric nitrogen oxides (NOx), produced by energetic electron precipitation (EEP), down to stratosphere during polar winter is expected to increase in the future due to acceleration of mean meridional circulation. In stratosphere, the transported NOx is known to contribute to the catalytic ozone losses in late winter and early spring.

In this study, we use Whole Atmosphere Community Climate Model with expanded D-region ion chemistry package (WACCM-D) to study the 21st century polar circulation and transport of mesospheric NOx during polar winter. Introduction of D-region ion chemistry reactions in the place of standard parameterization enhances the mesospheric production of NOx. The impact of the particle forcing recommended for the CMIP7 compared to the previous CMIP6 forcing is investigated.

## AS25-1201

# Solar energetic particle impact on mesospheric and stratospheric HNO3 over daily to decadal time scales

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The Whole Atmosphere Community Climate Model includes mesospheric ion chemistry and can be used to model the enhancements of nitric acid (HNO3) during particle precipitation events. WACCM-D has been shown to be in a good agreement with measurements during specific solar proton events. However, the longer-term variability of HNO3 has received much less attention. In this presentation, we investigate the enhancements of HNO3 during Energetic Electron Precipitation (EPP) events over daily to decadal time scales, using simulated data from WACCM-D. For example, we study the relation between HNO3 response and changes in the geomagnetic Ap index, providing insights into the relationship between the mesospheric/stratospheric regions and external forcing. These model results are validated against satellite-based HNO3 observations.

## AS25-1239

# Impact of negative ions in the ionization rate estimates obtained using EISCAT-VHF measurements

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In the polar latitudes, the energetic particle precipitation (EPP) causes enhanced ionization in the mesosphere-lower thermosphere region, which in turn greatly disturbs the chemical composition in the upper stratosphere through the mesosphere. The impact of these EPP events has been implemented in chemistry-climate models by including the particle forcing through ionization rate estimates obtained from satellites, ground-based instruments, rockets, etc. The negative ion chemistry plays an important role in the ionization rate calculations below 80 km, especially when estimating the fluxes of relativistic electrons. It is also crucial for accurately modeling the response of atmospheric composition to EPP. This study investigates the negative ion chemistry in the mesospheric altitudes using EISCAT-VHF spectral measurements carried out during solar proton events. Incoherent scatter radar (ISR) spectral measurements such as back-scattered power and spectral width are studied. Incoherent scatter (IS) spectral width carries information on negative ions, with increased negative ion density resulting in increased spectral width. As negative ions are destroyed by photo-detachment during sunlit hours, they can be observed in ISR measurements as a decrease/increase in spectral width during sunlit/dark hours. The observations of negative ions are compared with the Sodankylä Ion and neutral chemistry model results. Our study shows that negative ion chemistry plays an important role below 80 km in accurately estimating the electron densities from the IS spectrum and, therefore, can impact the ionization rate estimates when inverting the electron density profiles. The possible impact of negative ions in modeling the atmospheric response to EPP will be discussed.

## AS25-1352

# Reconstruction of energetic electron precipitation and atmospheric ionization for 1844–2023 using deep learning networks

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Reconstructions of energetic electron precipitation (EEP) and associated atmospheric ionization are important for state-of-the-art chemistry-climate models, which aim to model the climate impacts of EEP. The current version of the Coupled Model Inter-comparison Project, CMIP6, includes a reconstruction of EEP-induced ionization based on a parameterization dependent on geomagnetic Ap index. This reconstruction has been used in several climate studies over the past years. However, recent investigations have shown that the CMIP6 reconstruction underestimates the level of precipitation. Therefore, the atmospheric/climate impacts of EEP might be underestimated as well.

To address this issue we introduce here a new reconstruction of EEP and the ionization it produces. This reconstruction is based on a new composite of energetic electron measurements from POES satellites which have been corrected for various instrumental and sampling effects. A theoretically motivated form of a pitch angle distribution consistent with pitch angle diffusion is fitted to these data to obtain a more realistic estimate of electron precipitation into the atmosphere.

For the reconstruction we developed a deep learning network, which ingests homogenized geomagnetic aa index, sunspot number as well as seasonal variations and solar cycle phase. The network gives as output the daily latitude distributions of precipitating electron fluxes in three energy channels. This is then used to calculate the precipitating electron energy spectrum and associated atmospheric ionization from year 1844 to present.

Here we present the main aspects of this new reconstruction and also compare it with the earlier CMIP6 reconstruction.

## AS25-1369

# Energetic Electron Transport in the Inner Radiation Belt as a Source of Low-Latitude Precipitation

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Energetic electron injections below the inner radiation belt ($L \lesssim 1.2$) have been previously studied, with mechanisms such as large-scale electric fields playing a role in particle transport. Here, we analyse an event from September 2017, observed by the Van Allen Probes, to examine the dynamics of injected electrons in this region. Particle observations throughout the event are used as initial conditions for simulations to assess the potential for these electrons to precipitate into the atmosphere. Our results indicate that during this event, magnetospheric electric fields may have influenced electron precipitation by transporting particles across substantial radial distances. This study provides additional context for understanding low-latitude electron dynamics and the role of magnetospheric electric fields in modifying inner belt populations.

## AS25-1389

# The March 2012 weather extremes in Northeast America and Southeast Europe as possible effects of strong solar activity

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The present study examines in depth the possible influence of solar activity on the global weather extremes occurred in the first half of March 2012. In particular, we focus on the historic March 2012 heat wave in the Northeast United States (NE-USA) and the bad weather in Southwest (SW) Europe. To this end we examined data from various remote sensing instrumentation monitoring the Sun (SDO satellite), Interplanetary space (ACE / SOHO / PAMELA satellites), the Earth's magnetosphere (Earth-based measurements, NOAA-19 satellite), the top of the clouds (Terra and Aqua satellites), and the near ground atmosphere. The weather in NE-USA was characterized by extremely huge temperature increases $\Delta TM = 30^0$ (with maximum temperatures $TM = 28^0$) during a positive North Atlantic Oscillation index and large-scale warm air streaming from southern latitudes. On the contrary, Thrace (Northeast Greece) was characterized by a winter-like weather (rainfall, fast winds, decreased temperature) during an intense cyclonic circulation in Mediterranean. The global weather extremes in March 2012 were recorded during a superstorm caused by unexpected geoeffective interplanetary coronal mass ejections and intense streaming of solar protons of very high (>500 MeV) energies as recoded by SOHO and PAMELA. Furthermore, we note that the historic March 2012 and March 1910 heat waves (separated by one century) were related to Sun-generated special space plasma structures triggering large magnetic storms. We discuss the historic March 2012 heat wave in the NE-USA and the bad weather in SW-Europe in terms of solar cosmic rays influence on the low troposphere.

## A16 Mesosphere, Lower Thermosphere, and D-Region: Dynamics and Variability

### AS25-0072

# Effects of Energetic Particle Precipitation on the Lower Ionosphere Observed by Algiers-VLF Receivers

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Energetic particle precipitation (EPP) plays a significant role in modifying the ionosphere, mainly the D-region, by increasing ionization rate due to particle collisions. This study focuses on analyzing the impact of EPP observed during the strong geomagnetic storm of May 10, 2024 using Very Low Frequency (VLF) signal perturbations recorded by the Algiers VLF receivers. VLF signals propagate with a good efficiency through the Earth-ionosphere waveguide, making them highly sensitive to any modifications of the electron density. When energetic particles, principally electrons from the magnetosphere, precipitate into the lower ionosphere, they enhance ionization and modify the conductivity of the waveguide. These variations lead to detectable perturbations in the measured VLF signals, such as sudden phase and amplitude changes. By correlating the recorded VLF signal perturbations with in-situ particle flux measurements from NOAA and METOP satellites, it is possible to confirm the direct impact of EPP on the ionosphere. These satellites provide data on precipitating electron fluxes, allowing a spatio-temporal comparison between detected precipitation events and simultaneous VLF signal anomalies. The analysis of such coincidences helps to understand the extent and duration of ionospheric modifications caused by EPP. This approach provides valuable insights into space weather effects on the lower ionosphere and enhances the capability of VLF monitoring systems to detect particle precipitation events in real time.

## AS25-0073

# VLF Signal Analysis of Ionospheric Disturbances Triggered by the Tonga Eruption

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The eruption of the Hunga Tonga-Hunga Ha'apai volcano on 15 January 2022 generated major ionospheric disturbances in the form of Travelling Ionospheric Disturbances (TIDs). These waves propagated across the globe, travelling several times around the Earth. Algeria, whose deep south is located at the antipode of the eruption, is a key zone for observing these phenomena.

In this study, we analyze the VLF (Very Low Frequency) signals recorded in Boumerdès to assess the impact of the eruption on the ionosphere. VLF signals are sensitive to variations in ionospheric electron density, making them an effective tool for monitoring the dynamics of TIDs. Our results reveal clear wavy fluctuations in the amplitude of the VLF signals, with periods of between 30 seconds and 2 minutes, which coincide with the passage of the TID over the propagation paths of the VLF waves. These VLF signal perturbations are in close coincidence with also observed in the atmospheric pressure measurements fluctuations, suggesting a link between disturbances in the atmosphere and those in the ionosphere.

These results underline the value of VLF networks for monitoring interactions between extreme geophysical events and the ionosphere.

## AS25-0074

# Mediterranean D-region ionosphere response to solar flares events

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Solar flares significantly ionize the neutral atmosphere, leading to increases in the electron density of the ionosphere. This ionospheric disturbance impacts the Earth-Ionosphere waveguide, affecting electromagnetic signal propagation between transmitters and receivers. Such ionization-induced perturbations can be observed as fluctuations in the signal amplitude and phase and thus can be used to estimate the changes in electron density. In this study, we examine the response of the D-region of the lower ionosphere to solar flares by analyzing the Very Low Frequency (VLF) signals emitted by two separate transmitters in the Mediterranean Sea. By combining signal analysis with the Long Wave Propagation Capability (LWPC) code, we simulated the resulting signal perturbation parameters (amplitude and phase) and obtained an increase in electron density. This approach offers insights into the complex interactions between the solar flares and the ionosphere, which is important for communication and navigation systems.

## AS25-0121

# The effect of the SSW/ES event in 2018 on the VLF signal of three transmitter-receiver links in high latitudes

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Man-made radio signal transmissions with low frequencies (VLF, 3–30 kHz) travel from transmitter to receiver by being reflected between the Earth's surface and the bottom side of the ionosphere (D-region, 60–90 km). Since the D-region is the VLF's upper reflection boundary, its ionization perturbations are notable in the VLF signal amplitude. The highly variable ionization can be affected by atmospheric phenomena like Sudden Stratospheric Warmings (SSW) and Elevated Stratopause (ES) events. The atmospheric wave-driven SSW/ES events occur in mid-to-high latitudes and cause significant changes in wind, temperatures, and vertical mass transport. We studied the impact of the SSW/ES event in the winter of 2017/2018 on the VLF signal amplitude of three high-latitude transmitter-receiver (Tx-Rx) links. An increase in the amplitude during the SSW period could be observed for all three links. However, during the ES period, the amplitude variations differ between the Tx-Rx links. Only one link shows an amplitude decrease during the ES period, which was also observed for other ES events and seems to be a typical amplitude anomaly during an ES event under quiet solar and geomagnetic conditions. We found that the ES event in 2018 shows a substantial spatial variability. Thus, processes leading to the amplitude decrease during the ES period do not occur along all pathways to the same extent. We conclude that the differences between the VLF signal amplitude variations of the three links under consideration are caused by the spatial variability of the ES event in 2018.

## AS25-0128

# Dynamical Variability in the Mesosphere as seen in the Preliminary Version of the Extended NASA GEOS to the Lower Thermosphere

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The NASA Heliophysics and Earth Science Division of the Goddard Space Flight Center have partnered to develop an extension of the Goddard Earth Observing System (GEOS) to the lower thermosphere. In this talk, we present the motivations for this work that supports both heliophysics and Earth science domains and goals, the current status of the model development and discussion of some preliminary results. We present a set of simulations at different horizontal resolutions (1°, 0.5°, and 0.25°) in a vertical domain that extends to 150 km. We examine the large-scale structure of the atmospheric dynamics simulated by extended GEOS and the impact on tracer transports in the upper mesosphere and lower thermosphere using the GEOS dynamics to nudge the Whole Atmosphere Community Climate Model.

## AS25-0235

# Longitudinal development of high-energy electron precipitation at subauroral latitudes observed by the PWING riometer network

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The 30-MHz riometer can measure D-region ionization as cosmic noise absorption (CNA), which is caused by precipitation of electrons at energies of ~30–100 keV. Global distribution and development of CNA variation at subauroral latitudes have not been well understood. In this presentation, we report our recent results on the spatiotemporal development of CNA at subauroral latitudes using six ground-based 30-MHz riometers at subauroral latitudes in Canada, Alaska, Russia, and Iceland, based on the papers Kato et al. (JGR, 2024, https://doi.org/10.1029/2023JA032206) and Kato et al. (JGR, 2024, https://doi.org/10.1029/2023JA031950). These riometers were installed and operated by the PWING project (https://www.isee.nagoya-u.ac.jp/dimr/PWING/). We found that the spatio-temporal development of CNA at subauroral latitudes corresponds to high energy electron drift in the inner magnetosphere. The occurrence rate of steep increases in CNA is high at 22–08 MLT and low at 17–21 MLT. CNA at subauroral latitudes is closely related to solar wind and geomagnetic activities as well as storm-time substorms.

## AS25-0358

# Ionospheric D region: Understanding dawn and dusk characteristics for space weather monitoring capabilities

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Electron density characteristics of the Earth's ionospheric D-region, in the height range ~55–90 km, have been determined using phase and amplitude measurements of man-made, very low frequency (VLF) radio propagation in the Earth-ionosphere waveguide. Time variations of the 'Wait' height and sharpness parameters, H' and Beta, were identified through long-wave propagation modelling of VLF observations recorded over many years, and on many transmitter-receiver paths. This work was primarily undertaken by Neil Thomson, aided and abetted over the years by Craig Rodger and Mark Clilverd. Since 2010 Neil Thomson has led ten key papers describing the variation in H' and Beta over a wide range of relevant propagation situations, i.e., during the day, during the night, and over low-mid-high latitudes. Interpretation of the results illuminates the geophysical effects controlling D-region electron concentration profiles, including the dominant role of solar Lyman alpha at low and mid-latitudes, and the greater role of galactic cosmic rays at increasingly higher mid-latitudes.

In the most recent of the Thomson papers (in review), Wait parameters have been determined through dawn and dusk for the first time. The analysis provides H' and Beta values to constrain D-region modeling efforts, thereby extending the capabilities of VLF propagation monitoring for geophysical phenomena such as lightning, solar flares, and energetic particle precipitation. This talk summarises the recent work, focusing on dawn and dusk observations, and putting the resultant H' and Beta variations into context with day and night values, over a range of latitudes.

## AS25-0503

# Using atmospheric Waves for early Warning of natural Hazards: a Review combining Results from the neutral Atmosphere and the Ionosphere

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Waves transport energy through the atmosphere without transporting mass. Often excited in the troposphere, they can propagate horizontally and vertically over long distances, depending on the type of wave and the background atmosphere. The fastest atmospheric waves are (infra)sound and acoustic gravity waves.

The list of possible reasons for the generation of these atmospheric waves is not short; here, we concentrate on natural hazards. Due to their comparatively high propagation speed, infrasound and acoustic gravity waves can contribute to or even improve early warning of natural hazards, even when measured at high altitudes.

Traditionally, each scientific community—the one that deals with the neutral atmosphere and the one that addresses the ionosphere—usually works on its own. The aim of this contribution is to bring together observations and results from both communities. The main challenges of the respective communities with regard to the use of these waves in the context of early warning of natural hazards are identified.

## AS25-0651

# Contribution of gravity waves to the lower thermospheric winter-to-summer meridional circulation in high-resolution WACCM-X

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The mechanism of the lower thermospheric meridional circulation is analyzed using the high-resolution Whole Atmosphere Community Climate Model with thermosphere/ionosphere extension (WACCMX). In the winter lower thermosphere, a net eastward forcing is observed around z=120 km, consistent with the eastward wind and equatorward circulation. This is opposite to the westward forcing and eastward wind decrease in the upper mesosphere. Previous studies have indicated that small-scale waves have a large contribution to this wave forcing. In particular, the vertical flux of the horizontal momentum (u'w') accounts for most of the momentum flux deposition. Thus, the cause of the dominance of the eastward waves is examined.

From the wave decomposition analysis, eastward waves with a wide range of phase speed are generated at the height of the strong eastward wind. It is also confirmed that the horizontal distribution of these waves is associated with the topography. Thus, these waves are considered to be secondary orographic gravity waves. This result is different from the understanding in the conventional gravity wave parameterizations that eastward waves cannot propagate above the critical level in the strong eastward wind. On the other hand, quasi-stationary and westward waves are also active in the mesosphere, while some of them propagate from the troposphere. However, these waves are more dissipated at a critical level and westward shear during propagation in the upper mesosphere. Therefore, the in-situ generation and the difference in propagation influenced by the zonal wind profile are key to the lower thermospheric eastward forcing.

## AS25-0991

# The Antarctic Gravity Waves Instrument Network: Investigating Mesospheric Gravity Waves over Antarctica

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The ANtarctic Gravity Wave Instrument Network (ANGWIN) is an international collaboration initiated in 2012 to operate a network of ground-based instruments around the Antarctic Continent in order to investigate the propagation and effects of gravity waves in the upper atmosphere. This program provides excellent opportunities to engage scientists and students from around the world, with collaborative research opportunities, data and analysis tool sharing, student exchange, focused scientific workshops, and joint research publications.

As part of ANGWIN, Utah State University (USU) has deployed infrared all-sky imagers (ASI) at several locations around the continent. Horizontal measurements of gravity waves at the altitude of the hydroxyl (OH) layer (~87 km) have been conducted from McMurdo (77.8° S), Davis (68.6° S), Halley (75.6° S), and Rothera (67.6° S) stations every winter season for the past 12 years.

The images obtained every 10 seconds have been processed first using a machine learning algorithm to select periods of clear sky (no cloud, aurora or moonlight) longer than two hours, then the corresponding power spectra have been generated, following the M-transform method defined by Matsuda et al., 2014.

This contribution will present the ANGWIN project, then describe the ASI airglow data and the analysis processes. It will subsequently reveal the year-to-year and geographical variabilities, as well as the evolution of small-scale gravity wave power during the winter season, providing an overview of the mesospheric gravity wave activity above Antarctica over the duration of a solar cycle.

## AS25-1129

# The Atmospheric Waves Experiment (AWE)

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Modern theory and modeling indicate that atmospheric gravity waves (AGWs) play an important role in vertical coupling of the atmosphere-ionosphere system. Although small-scale AGWs (horizontal wavelengths ~30–300 km) are thought to account for the dominant energy and momentum inputs at Ionosphere-Thermosphere-Mesosphere (ITM) altitudes, the sources, variability, and influences of small-scale AGWs are still major unknowns. NASA's Atmospheric Waves Experiment (AWE) mission is a Heliophysics Small Explorers Mission of Opportunity designed to investigate how terrestrial weather affects space weather, via small-scale AGWs produced in Earth's atmosphere. Installed on the International Space Station (ISS) in November 2023, AWE began its 2-year mission to explore global distribution of AGWs, study processes controlling their propagation throughout the upper atmosphere, and estimate their impacts on the ITM system. The AWE science instrument consists of an Advanced Mesospheric Temperature Mapper (AMTM) that quantifies gravity wave-induced temperature disturbances in the hydroxyl (OH) airglow layer (~87 km altitude). The AMTM's four identical telescopes make continuous nighttime observations of the $P_1(2)$ and $P_1(4)$ emission lines of the OH (3,1) band, the $Q_1(1)$ emission line in the OH (2,0) band, and the atmospheric background from which the OH layer temperature is derived. AWE images are collected once per second, co-added, and processed into intensity and temperature swaths using correction algorithms derived from ground calibration test results. OH layer Global coverage is provided every four days, enabling regional and seasonal studies, and characterization of AGW 'hot spots.' This paper provides an overview of the AWE mission and discuss initial results.

# A17 Atmospheric responses to total and annular solar eclipses and transient events

## AS25-0623

## Spectral analysis of gravity waves observed in different airglow emissions during the 14 October 2023 eclipse over Brazil

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Although gravity waves are widely studied, their generation associated with solar eclipses remains poorly studied in the scientific literature due to the low frequency of such events. Gravity waves were observed during the 14 October 2023 solar annular eclipse using OH, OI5577, O2(0,1) and OI6300 airglow emissions. The spectral characteristics of these oscillations were analysed using data obtained from three different sites in Brazil: São João do Cariri, PB (7.4° S,36.5° W), Bom Jesus da Lapa, BA (13.15° S,43.25° W), and Santarém, PA (2.26° S,54.42° W). As a result, gravity waves exhibiting small and medium-scale spectral characteristics were identified. In Cariri, it was observed gravity wave with a horizontal wavelength of 171 km, a period of 52.4 min, a phase velocity of 54.4 m/s, and an eastward propagation direction. In Santarém, a wave was detected in the emissions of OH, OI5577, and OI6300 and had a horizontal wavelength of 719.6 km, a period of 127.2 min, a phase velocity of 94.3 m/s, and a northeastward direction. At the Bom Jesus, a wave with a horizontal wavelength of 173.1 km, a period of 49.3 min, and a phase velocity of 58.5 m/s propagating eastward in both OH and OI5577. Notably, the waves detected in different stations in Brazil exhibit characteristics consistent with a potential source consistent with the trajectory of the eclipse in Earth's atmosphere.

## AS25-0774

# The 2024 Total Solar Eclipse and Resulting Interhemispheric Ionospheric Currents

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Total Solar Eclipses have a significant influence on Earth's atmosphere. The Moon's footprint on Earth's surface disturb the solar extreme ultra violet (EUV) and X-ray radiations, in addition to the visible light. The blocked EUV/X-ray radiation creates a decrease in the E-region conductivity. As a result of this E-region conductivity decrease, other regions of the ionosphere seek to restore equilibrium, creating an interhemispheric current. In this presentation, we will feature a set of NCAR Specified Dynamics Whole Atmosphere Community Climate Model with thermosphere and ionosphere eXtension (SD-WACCM-X) runs with a mask that accurately replicates the solar radiation and its gradients around the eclipse. We will show the effects of this decrease in conductivity, the eclipse-related currents, and the expected magnetic field perturbations one should expect on the ground. Preliminary results show that the magnetic perturbations are larger than 10 nT, which is well within the measurable range for ground magnetometers. This presentation will also feature observed ground magnetic perturbations to evaluate the simulation and present results.

## AS25-1209

# Effects on gamma-ray flux during eclipses and various terrestrial events

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Secondary cosmic rays (SCRs) such as neutrons, gamma rays, muons, pions, electrons, etc. are produced in the Earth's atmosphere when primary cosmic ray particle collide with the atmospheric particles. The gamma ray flux measured at a particular location is affected by many factors and transient space weather, terrestrial and astronomical phenomena. The effects of solar and lunar eclipses on gamma-ray data recorded by NaI(Tl) scintillation detector located at Tirunelveli, India are investigated here when the observation site was in the shadow region. Gamma-ray flux is found to have some effect during solar eclipses, while no change is observed during lunar eclipses. Also, the gamma ray response to the Cyclone Ockhi is investigated. It is found that the low energy gamma rays are significantly affected by the cyclone dynamics, while high energy gamma rays are unaffected. The thunderstorm ground enhancements (TGE) in gamma rays are also investigated. The responsible atmospheric dynamics will be discussed.

## AS25-1291

# Ground-based imaging spectrographic observations of sky emissions during the April 8, 2024 total solar eclipse

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A long-slit imaging spectrograph was used to simultaneously observe O I 5577Å, O I 6300Å, Hα 6563Å and Hβ 4861Å emissions from the upper atmosphere during the total solar eclipse of April 08, 2024. The spectrograph called, HiT&MIS, has a field-of-view of 0.5˚ X 16˚, an imaging resolution of 0.1° and a spectral resolving power of 7,000. It observed the eclipse from North Hero, Vermont (44.83° N, 73.27° W), where the totality lasted for approximately 3.5 minutes.

Near the totality at 15:27 local time (19:27 UTC), the Sun was approximately at 233˚ SW azimuth and 40˚ elevation. The slit of the instrument was pointed along 230˚ SW in azimuth and covered 52˚ to 68˚ elevation angles. Using an automatic exposure algorithm to compensate for the change in sky brightness, the instrument captured the evolution of sky spectra for several hours including the eclipse period.

During totality, the O I 6300Å and Hα 6563Å emission features were seen as emission lines thus, brighter than the ambient sky. The O I 5577Å and Hβ 4861Å emissions were also observed as they filled-in the absorption lines. O I 5577Å and O I 6300Å airglow have been observed during day and night time. The detection of Hα 6563Å and Hβ 4861Å emissions and their temporal evolution during the sudden removal and reappearance of the solar input is novel and require careful consideration of their origin in the specific observation scenario.

## AS25-1359

# Characteristics of vertically propagating gravity waves under various background conditions

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Vertical propagation of atmospheric gravity waves (GWs) is studied at São João do Cariri (7.40° S, 36.31° W), Brazil, using photometer, all-sky imager, and meteor radar. Airglow emission intensities, atomic oxygen green line (OI 557.7 nm), molecular oxygen ($O_2$ (0–1)), sodium D-line (NaD), and hydroxyl (OH (6–2)) measured by photometer were used to investigate the vertical propagation characteristics of GWs with similar periods across these emission layers. Using OH airglow images, the horizontal parameters of the same GWs were determined and subsequently their intrinsic parameters using simultaneous horizontal winds by meteor radar. Using the phase of the GWs across each emission layer, the phase progression exhibited downward, upward and near-vertical propagation under different background propagation conditions. This indicates that background propagation conditions significantly control the vertical propagation of GWs.

## AS25-1446

# Possible effects of 7-10d oscillation in the precipitation over Campina Grande in 2022

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Using data collected by the Instituto Nacional de Meteorologia (INMET) over Campina Grande (7.22ºS, 35.88ºW), 1026 mm of precipitation was recorded in 2022, which is 35% more than it was observed in the past 10 years. Additionally, along the year the great values of precipitation occurred in the rainy season from May to July, but it was also greater then the historical average for this period. In order to investigate this behaviour, the Lomb-Scargle analysis was performed in the precipitation data and a strong 9–10 days peak was found. Investigating this periodic oscillation in other parameters like meridional and zonal wind, pressure and temperature, evidence of oscillation of 7–10 days was also observed around this event. Furthermore, zonal and meridional wind in the mesosphere and lower thermosphere (MLT) measured by an meteor radar deployed in São João do Cariri (7,4ºS, 36.5ºW) were also studied and revealed the presence of ~8 days oscillation more pronounced in the zonal component. It suggests that a fast elvin wave could be present in the MLT and could be either the main cause of this anomalous precipitation over Campina Grande or the precipitation could produce the Kelvin wave. More analysis is necessary to advance in this topic.

## AS25-1447

# Effects of the 14 October 2023 annular solar eclipse on the atmospheric temperature

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Using temperature and pressure profiles measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on board the Thermosphere Ionosphere Mesosphere Energetics Dynamics(TIMED) satellite, possible effects of the passage of the 14 October2023 solar annular eclipse were investigated. SABER profiles almost simultaneously with the crossing the path of the Moon's shadow over the central and south Americas were used. The investigation was focused on possible changes in the temperature and pressure of the mesosphere and lower thermosphere, i.e., from 80 to 110 km. It has been observed turbulent patterns which could be associated with waves generated by the eclipse. Salient aspects of the observation are discussed based on the comparison to days before and after the eclipse, which reveals that the solar eclipses can significantly change the behavior of the background atmosphere.

# A18 Div III Reporter Review (invitation only)

## AS25-0107
## Magnetotail Dynamics

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Over the past two years, the magnetotail research has been expanded by data from the new missions, new analyses of existing mission data, new empirical reconstructions using archives of data from 1995 and earlier, as well as new advances in theory, simulations and "grey-box" algorithms combining first-principles simulations and data. ELFIN observations provided a new global view of the of the tail through observations of the isotropic precipitation boundaries, whose comparison with empirical magnetic field reconstructions helped improve the latter. ELFIN and CIRBE observations revealed regions of relativistic electron generation in the magnetotail plasma sheet challenging conventional scenarios. MMS observations helped estimate new kinetic parameters of the plasma dissipation in the magnetotail reconnection. ARTEMIS observations revealed the regular structure of the magnetic field at lunar distances supported by the ion-scale thin current sheets. THEMIS observations led to the discovery of X-lines located much closer to the Earth compared to earlier studies. Data mining-based empirical reconstructions resolved most X-lines detected by MMS as well as very near-Earth reconnection regions for extreme magnetic storms. Global hybrid and PIC simulations revealed the importance of flapping motions in the substorm onset and magnetic reconnection. New kinetic models of force-free and overstretched tail current sheets have been elaborated and supported by PIC simulations. Grey-box models combining global empirical reconstructions of the magnetosphere with its global MHD simulations are shown to nudge the latter to start magnetic reconnection at the right time and in the right place. Other findings and open questions will also be discussed.

## AS25-0690

# Reporter review on waves in the Earth's magnetosphere

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The Earth's magnetosphere is subjected to constant bombardment of solar wind and interplanetary magnetic field (IMF) from the Sun which compresses its dayside field lines and stretches the night side into magnetotail. The dayside and night side reconnection of the magnetic field lines pave way for transfer of mass, energy and momentum into the Earth's magnetosphere which makes it highly dynamic. A plethora of plasma waves are generated in the Earth's magnetosphere due to the fluctuations in the electric and magnetic fields and the plasma contained therein. This talk is focused on the review of recent advances in the field of study of these waves and how far we have come in understanding the complex magnetospheric processes.

## AS25-1208

# Reporter review: dayside magnetopshere and boundary layers

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Dayside magnetosphere and boundary layers are the regions where solar wind directly interacts with the Earth's magnetic field, playing an essential role in the energy and mass transportation into the magnetosphere. This reporter review presents the most recent scientific advances in this field during the past two years. The topics include but are not limited to, large-scale morphology of dayside magnetopause and cusps expected to be observed by imaging missions such as SMILE, small-scale or transient structures measured by in-situ satellites such as MMS, and the dynamic coupling to the ionosphere as well as their geo-effects. Highlights in numerical simulations will also be reviewed in this talk.

## AS25-1271

# Reporter review: magnetosphere-ionosphere coupling

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Couplings in the magnetosphere-ionosphere (M-I) link a broad range of spatio-temporal scales and "activate" a large portfolio of physical processes, among which energy precipitation, sheared plasma flows, discrete aurora, parallel electric fields, field-aligned currents, electromagnetic and plasma waves (in the kinetic and MHD regime). The strength of the coupling changes during disturbed times. Quiet times phenomenology still remains a challenge for modelers and data analysis. The coupling is bidirectional, with the magnetosphere generally playing the role of generator and the ionosphere-thermosphere the role of energy dissipator and also providing feedback in the system. Spacecraft at lower altitudes, such as GOLD, or at the higher magnetospheric side (e.g., Cluster, MMS, THEMIS) probe in-situ key regions of the coupled system at quiet and disturbed times. Observations from the ground, like auroral and magnetic observatories, radars, iono- and dyna-sondes, provide data which help illuminating the complex M-I interactions and couplings. Evolved numerical modelling and simulations complete the portfolio of methodologies applied to reveal the physical processes active in the M-I coupling. This talk highlights recent advances in understanding the magnetosphere-ionosphere coupling and the effect of disturbed times.

## AS25-1353

# Reporter review on inner magnetosphere dynamics and coupling

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The inner magnetosphere is a critical region of geospace, but is challenging to understand due to its complexity. It is host to a variety of plasma and wave populations that shape and are shaped by their interconnected evolution with the magnetotail, ionosphere, and exosphere. In this presentation, we review advances in the understanding of inner magnetosphere dynamics and coupling made in the past two years via observations from previous and ongoing missions, and results from well-established and emerging numerical models. Topics include transport to the ring current via bursty bulk flows and near-Earth reconnection, transport and energization of heavy ions, statistical properties and drivers of waves and precipitation, auroral signatures and geomagnetic consequences of deeply-penetrating injections, and advances and gaps in our understanding of ring current loss processes.

## AS25-1422

# Reporter review: Recent advances in giant planet magnetospheric dynamics

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While we know much less about the giant planet magnetospheres than the Earth,it is becoming clear that their dynamics are very different from terrestrial processes. At Jupiter the Juno mission is revealing a plasma disk that is spatially and temporallyvariable. But the relative importance—and coupling between—internal and externalprocesses is a struggle to untangle. The smaller, less powerful system at Saturnis somewhat simpler to characterize. With just the Voyager 2 flybys of Uranusand Neptune (1986, 1989) gave brief glimpses of highly irregular magnetospheres. The possibility of a potential Uranus orbiter has revived interest in thesemagnetospheres and provoked speculation of what a future mission might find. In this review we will summarize the range of ideas about giant planetmagnetospheric dynamics and progress made in the past 2 years.

## AS25-1448

# Reporter Review: Advances in the Radiation Belt Studies in the Recent Two Years

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This talk reviews the progreses of rediation belt research in the year 2023–2025. We present highlights of studies of the radiation belt enhancement and decay dynamics. The topics include: wave-particle interactions, empirical wave modeling, particle precipitation, magnetopause shadowing and etc. We present studies that use observations, modeling and comparisons between model results and observations.

# A20 Magnetosphere-ionosphere-thermosphere coupling, new insights from data, numerical simulations and models

## AS25-0054

## Development of the Chinese Dual Auroral Radar Network and Preliminary Results

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Led by the National Space Science Center of the Chinese Academy of Sciences, we have built a Chinese dual auroral radar network in northern China, which is called the CN-DARN. The CN-DARN consists of three pairs of high-frequency coherent scattering radar facilities and is one of the key parts of the Chinese Meridian Project Phase II. It has been fully constructed and started trial operations at the end of 2023. The detection range of the radar network extends longitudinally over approximately 9 hr of local times and covers the middle to high latitudes of the entire Asia region above 40°. In this paper, we present the basic design of the CN-DARN and its preliminary observations of ionospheric irregularities, subauroral polarization streams (SAPSs) and traveling ionospheric disturbances (TIDs). We also investigate its contribution to the ionospheric convection pattern of the Northern Hemisphere derived from Super Dual Auroral Radar Network (SuperDARN) observations. The results indicate that the CN-DARN provides excellent measurements and better specifications of flows in the Asian sector, improving our understanding of the global-scale ionospheric convection pattern in the Northern Hemisphere. These encouraging results lead us to believe that the CN-DARN will play an important role in studies on the evolution of ionospheric irregularities, the characteristics and evolution of SAPSs, the propagation of TIDs, and global-scale ionospheric convection dynamics.

## AS25-0154

# Variation of the Equatorial Electrojet from Swarm Data in China Sector

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The daytime ionospheric E region (90–120 km), where dynamo processes generate an eastward electric field, is a critical area for studying equatorial electrojet (EEJ) activity. This eastward electric field at the dip equator drives vertical E × B electron drift, leading to polarization charge accumulation at the E region boundaries and the formation of an upward polarization electric field. This field drives a strong eastward electric current on the day side, creating the EEJ—a narrow band of enhanced electric activity along the dip equator in the ionospheric E region.

The Swarm satellites provide high-quality geomagnetic measurements globally. In this study, data from the Swarm A and C satellites near 115° longitude were analyzed to investigate the EEJ effect during solar high-activity years (2014–2015) and low-activity years (2018–2019). Data were selected with Kp ≤ 2 and divided into Lloyd seasons. Using the CHAOS model, the main and crustal geomagnetic fields were removed, and the remaining data were converted to the dipole geomagnetic coordinate system to get the H component (northward at the dip equator).

For each season, the H component was analyzed using 1° × 0.25-hour resolution bins in geomagnetic latitude and local time. A background Sq signal was subtracted outside a ±12° window around the dip equator to obtain a clean EEJ signal. This approach allowed the investigation of EEJ characteristics across different seasons and solar activity levels.

## AS25-0223

# GOLD Observations of the Thermosphere-Ionosphere Response to the 10–12 May 2024 Gannon Superstorm

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After days of intense solar activity, active region AR3664 launched seven CMEs toward Earth, producing an extreme G5 geomagnetic storm commencing at 17:05 UT on 10 May 2024. The storm impacted power grids, disrupted precision navigational systems used by farming equipment, and generated aurora seen around the globe. The storm produced remarkable effects on composition, temperature, and dynamics in the Earth's thermosphere and ionosphere that were observed by NASA's Global-scale Observations of the Limb and Disk (GOLD)mission. Approximately 6 hours after the storm commenced, the nightside southern crest of the Equatorial Ionization Anomaly (EIA) was observed to merge with the aurora near the southern tip of South America. Approximately 17 hours after commencement synoptic disk images of ΣO/N2 and neutral temperature (at ~160 km) at the same longitudes directly link dynamics resulting from the storm with dramatic changes in thermospheric composition and temperature. Equator-to-pole temperature differences reach 400 K with high latitude peak neutral temperatures near 160 km exceeding 1400 K. On both the nightside and dayside GOLD observed spatial morphology without precedent in reported observations of the dayside ΣO/N2 and neutral temperature or the EIA. These observations and the subsequent identification of similar dayside thermospheric changes in GOLD observations of other storms offer insights into the thermosphere-ionosphere response to extreme geomagnetic disturbances, highlighting the complex interplay between solar activity and Earth's upper atmosphere.

## AS25-0225

# Resonant vibrational excitation of nitrogen (N2) and STEVE

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The term Strong Thermal Emission Velocity Enhancement (STEVE) refers to a distinct form of continuum optical emission, an east-to-west ribbon of mauve light in the sub-auroral, near-midnight sky. Its underlying formation mechanisms are presently unresolved. Using laboratory measurements of electron-molecule collisions, and published observations of STEVE, we investigate the resonant vibrational excitation (RVE) of nitrogen ($N_2$) via the $^2\Pi_g$ resonance by low-energy (~2–4 eV) electron impact, and its effectiveness under the prevailing plasma conditions in the E- and lower F-region. Inside a Sub-Auroral Ion Drift (SAID) region at elevated electron temperature (with an increased fraction of >2-eV electrons), RVE is found to constitute the dominant underlying mechanism for STEVE: it rapidly increases the $N_2$ population at and above the v=10 vibrational level, leading to the subsequent formation of $N_2O$ via radiative attachment and associated visible continuum emission. We present a kinetic-photochemical model for the dynamic evolution of the detailed vibrational distribution and the ensuing continuum volume emission rate (VER). In a region of SAID at an elevated electron temperature $T_e$ of 4000–6000 K over a latitudinal width of 20 km, our model predicts (a) an orders-of-magnitude increase in the vibrationally excited ($v \geq 10$) $N_2$ density within ~10 minutes of substorm expansion onset, and (b) the increase in peak continuum emission brightness from <1 kilo-Raileigh (kR) at $T_e$ = 4000 K to to ~10 kR at $T_e$ = 6000 K. These predictions compare well with the statistical characteristics of observed STEVE events.

## AS25-0234

# Plasma and electromagnetic field characteristics in the source region of STEVE and SAR arcs in the inner magnetosphere

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The STEVE and Stable Auroral Red (SAR) arcs are characteristic auroral arcs that appear at subauroral latitudes just equatorward of the auroral oval. Characteristics of plasma and electromagnetic fields in the magnetospheric source region of these arcs have not been understood well. In this presentation, we report our recent results on the multi-event analysis of these arcs using data from ground optical and radio instruments and the Arase and Van Allen Probes satellites, based on Sugimura et al. (JGR, 2025, https://doi.org/10.1029/2024JA032793). We also report a subsequent statistical study of Van Allen Probes-B observations of SAR arc intervals in the overlap region between the plasmasphere and the ring current, based on Sugimura et al. (JGR, 2025, https://doi.org/10.1029/2024JA032893). These two recently-published papers clarify the characteristics of plasma and electromagnetic fields in the source region of STEVE and SAR arcs and the global distribution of SAR arc source region in the inner magnetosphere.

## AS25-0323

# Fabry Perot observations of the thermospheric winds using various retrieval methods over Tenerife

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Thermospheric winds play a crucial role in the transport of momentum and energy in the upper atmosphere which affects the composition and the dynamics of the thermosphere and ionosphere. Understanding thermospheric winds is key for improving satellite operations and global communication systems. An important tool for measuring the thermospheric winds is the Fabry Pérot Interferometer (FPI). The FPI is a remote sensing instrument whose measurement principle relies on an etalon, consisting of two parallel, partially reflective surfaces, producing constructive interference under specific conditions.

FPIs are used to image naturally occurring airglow emission lines with well-known spectral characteristics. The resulting images are analyzed to infer temperature and line-of-sight wind. The key mechanism for the retrieval of these physical parameters is the use of the Doppler-broadening and Doppler shift of airglow emission, respectively. In March 2024, DLR installed a new, own construction of a 630 nm FPI on Tenerife (SOFPIT) at geographical coordinates 28.29° N, 16.63° W and geomagnetical coordinates 32.79° N, 60.75° E. SOFPIT delivered almost a full year of thermosphere wind observations during night conditions. Methods for deriving winds and temperatures have been developed based on instrument specifics. Comparisons with the horizontal wind model (HWM) confirm that initial SOFPIT wind observations are in the correct order of magnitude.

Using data from SOFPIT, a comparison between retrieval methods is performed. Assessments of the underlying assumptions on the dynamics of the atmosphere (zero-wind reference, constant vertical wind and uniform horizontal wind over a period of time) are made. A data model comparison is implemented.

## AS25-0379

# Determination of shell currents pattern in the ionosphere from measurements of field aligned currents

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[1] provides field aligned current (FAC) density and electric potential above the ionosphere. [2,3] demonstrated that the magnetic field induced by FAC can be calculated from Weimer's model output. Below the ionosphere, the FACs induced magnetic field is not present because of the shell (closure) currents in the ionosphere. In this work, we deduce from the magnetic field jump in the ionosphere the magnitude and direction of the shell current at any point in the ionosphere. And the global pattern of the shell current is reconstructed. Next, the conductivity tensor at any location is found based on electrical potential data [1] and calculated shell currents. The method has been developed and used in [4] for surface currents on the boundary of a toroidal magnetic cloud in the solar wind and later also applied for surface currents on Earth's magnetopause and bow shock [5]. This research is supported by the NSF grant 2230363. M. V. acknowledges support from the AV CR grant RVO:67985815.

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## AS25-0386

# Magnetosphere-Ionosphere Coupling in the auroral zones of Earth and Jupiter

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The Juno satellite, in polar orbit around Jupiter, has allowed for the first comparison of particles and fields between the Earth and Jupiter. These two auroral zones have many similarities but are distinct in other ways. Both auroral zones show monoenergetic acceleration of electrons as well as broadband acceleration; however, at Jupiter the broadband acceleration is dominant, as opposed to Earth. In addition, the downward current region at Jupiter is a region of bright aurora due to the bidirectional, broadband acceleration of electrons. In both magnetospheres, coupling to the ionosphere is important in the evolution of auroral currents and fields. Somewhat surprisingly, the density and temperature of the Jovian ionosphere is similar to that of Earth; however, the composition is quite different, with Jupiter's ionosphere largely consisting of protons with the second most common ion being $H_3^+$. In both magnetospheres, the rapid drop in plasma density in the topside ionosphere leads to an Ionospheric Alfven Resonator that can structure the currents in the 1 Hz range. These regions can be investigated with a combination of fluid and test particle simulations. Of particular interest at Jupiter is the coupling of the moon Io to the magnetosphere and ionosphere, leading to an extended auroral tail consisting of multiple subspots.

## AS25-0523

# New magnetospheric insights from a decade of Terrestrial Radio Emissions

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The Earth's radio emissions are a very valuable remote diagnostic of magnetospheric dynamics. Auroral Kilometric Radiation (AKR) is Earth's strongest natural radio emission, and is anisotropically beamed from a source locked to auroral latitude magnetic field lines. These field lines trace through the auroral acceleration region down to the ionosphere, and following substorm onset, the electron population in this region may stimulate AKR along with auroral effects. Here we present new insights from a decadal archive of AKR observations from spacecraft including Wind/WAVES, and discuss future applications.

## AS25-0541

# Magnetosphere-ionosphere coupling at the plasma boundary layer/ subauroral ionosphere

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Magnetosphere-ionosphere coupling in the sub-auroral region plays a crucial role in the dynamic evolution of Geospace plasma dynamics, particularly during geomagnetic storms and substorms. A key feature of this coupling is the sub-auroral polarization stream (SAPS) associated mesoscale electric field. The SAPS electric field contributes to the formation of the mid-latitude ionospheric trough and the erosion of the plasmasphere. The relationship between the plasma boundary layer (PBL), including the plasmapause, and various ionospheric phenomena has been studied for decades. Despite prolonged efforts, many details of these relationships and the mechanisms underlying them remain poorly understood.

ESA's Swarm mission, in conjunction with magnetospheric missions such as RBSP and Arase, provides an unprecedented opportunity to study these relationships on a global scale over an extended time period. Swarm delivers observations of midlatitude ionospheric trough (MIT), the associated sub-auroral electron temperature enhancement (SETE), while PBL crossings can be inferred from in-situ magnetospheric electron density measurements.

In this study, we utilise conjugated Swarm and in-situ PBL observations from 2014 to 2019 to address some of the unresolved questions. We previously confirmed that MIT/SETE and PBL are directly coupled on the nightside [1]. Their correlation remains strong after post-dawn, although with an increasing, MLT-dependent time lag. Our findings support the scenario that the plasmapause forms on the nightside and propagates to the dayside by co-rotating with the Earth. We now extend our earlier investigations to explore the less-studied afternoon MLT range.

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## AS25-0551

# Electron density variation in the plasmasphere and ionosphere during the May 2024 super geomagnetic storm

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We analyzed Global Navigation Satellite System—total electron content (TEC) and Arase satellite observation data to elucidate the cause of the electron density variation in the plasmasphere and ionosphere during the May 2024 storm. For identification of the electron density variation in the ionosphere, we calculated the ratio of the TEC difference (rTEC) defined as a difference from a 10 quiet-day average TEC normalized by the average value. Further, we derived the electron density in the plasmasphere and inner magnetosphere from the upper limit frequency of upper-hybrid resonance (UHR) waves observed by the Arase satellite. As a result, an L-t diagram of the electron density shows a shrink of the plasmasphere from L=7.0 to L=2.0 associated with the storm onset. After the onset of the storm recovery phase, the plasmapause moved slowly to the higher L-value and recovered the level of geomagnetically quiet times on a 4-day scale. The time scale of the plasmaspheric refilling is much longer than that of other coronal mass ejection-driven storms. On the other hand, several polar maps of rTEC during the storm show that a large depletion of the rTEC value from the high to low latitudes during the storm recovery phase. The depletion suggests the occurrence of a negative storm due to the neutral composition ($O/N_2$) change driven by energy input from the magnetosphere at the high-latitude thermosphere. Therefore, the contribution of a negative storm to the plasmaspheric refilling process should be included in the plasmaspheric and inner magnetospheric models.

## AS25-0618

# Kinetic properties of magnetospheric generators at the origin of quasi-steady auroral arcs observed by the ASIS spectrograph

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The ASIS (Auroral Spectrograph In Skibotn) instrument has been installed at the Skibotn observatory in Norway in October 2023. It has accumulated auroral spectra during two consecutive winter seasons with a spectral resolution of ~ 0.4 nm and a wavelength range of ~ [400–700] nm. Incoming light is captured in a FOV of ~ 4°, centered on the local magnetic field line. Time resolution is 30 seconds. In this study, we select a few cases when quasi-steady auroral arcs were in the FOV of ASIS. Selection is done manually after a first pre-selection based on the automatic AI classification of an all-sky camera also located at the Skibotn observatory. The characteristic energy of precipitating electrons can be obtained either by computing line ratios or using synthetic spectra.

BIRA-IASB has developed a magnetospheric-ionospheric (M-I) coupling model which links the properties of quasi-stationary auroral arc with those of a magnetospheric generator, usually described by a Vlasov equilibrium solution for a tangential plasma interface. The model can provide the characteristic energy of precipitating electrons when a velocity distribution function is assumed in the magnetospheric generator and the field-aligned potential drop is known. A recent application of the model solved an "inverse" problem, i.e. find the magnetospheric generator plasma state that is the most compatible with e.g. ground-based observations of stationary arcs. We present the first attempt to use the M-I coupling modelling with data from the ASIS spectrograph and estimate the kinetic properties of the magnetospheric generator.

## AS25-0673

# Ionospheric/Thermosphere Coupling, Dynamics, and Timing During Ionospheric Storms

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During geomagnetic storms, several processes occur in the upper thermosphere and ionosphere that lead to rapid changes in the structure and dynamics of those regions. In the ionosphere, these changes are termed ionospheric storms and are known to have a positive phase (or positive ionospheric storm), generally occurring during the main phase of a geomagnetic storm, followed by an extended negative phase (or negative ionospheric storm) generally occurring during the storm recovery phase During these phases at midlatitudes, the F2 region density, the location of the F2 region peak density, and the Total Electron Content (TEC) increase (positive phase) and decrease (negative phase) much below their normal levels. We present comprehensive measurements of the ionosphere and thermosphere from multiple satellite and ground-based observations during a geomagnetic storm on September 26, 2011. The database includes plasma composition, drifts and temperatures from the Defense Meteorological Satellite Program (DMSP) and the Communication/Navigation and Outage Forecast System (CNOFS) satellites, TEC measurements from ground-based Global Positioning System (GPS) observations, neutral wind, density, and TEC measurements from the Gravity field and Ocean Circulation Explorer (GOCE) satellite, TEC measurements from the Gravity Recovery and Climate Experiment (GRACE) satellite, and thermospheric $O/N_2$ ratio measurements from the DMSP Special Sensor Ultraviolet Spectrographic Imagers (SSUSI). We discuss the observations in terms of the timing of and the proposed mechanisms for the development of the positive and negative phases of ionospheric storms.

## AS25-0782

# Validation Framework to Study the Solar Forcing in the Context of Ionospheric Modelling

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The ionosphere reaches its highest electron density (NmF2) at around an altitude of 250–300 km (hmF2) and it affects the electrical conductivity in that region. Space weather (SW) events can alter electron density in the ionosphere which could lead to signal disruption, reducing transmission quality and position precision in Global Navigation Satellite System (GNSS). The growing importance of GNSS based systems in nowadays society drives the need for more accurate and reliable Thermosphere—Ionosphere (TI) forecasts. In order to understand the TI modelling current state and improvements, model validation studies have been addressing the results of models around quiet and disturbed geomagnetic periods using quantitative metrics. In this study, the resulting NmF2 from a set of physics based models, is evaluated for the first time against Ionospheric radio occultation data from the COSMIC2 mission, as well as ionosonde data from 70 stations from the Global Ionosphere Radio Observatory (GIRO). Eight periods of twenty days through 2020 (near solar minimum) and 2024 (near solar maximum) are included in the analysis in order to cover most of the ionospheric variability such as the solar cycle, solar rotation, daily, seasonal and local features. The validation framework is composed of statistical methods such as the Correlation coefficient, Root Mean Square error and prediction efficiency. The results allow a comparison between models and a quantification of the improvement between different model versions. The output of this work will be used to develop, optimize and evaluate TI model ensembles.

## AS25-0792

# Cluster plasmapause locations—first results obtained using developed graphical user interface

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The results of preliminary tests performed with the graphical user interface (GUI) that we developed have shown that it has great potential for determining plasmapause positions (PP), as far as possible based on CLUSTER satellites for the period 2002–2018. The electron densities obtained from the WHISTLER instrument, spacecraft potential obtained from EFW instrument, magnetic field measured by FGM, satellite position, L-shell parameter, and WHISPER spectrograms from Cluster Science Archive were used. The PP using GUI were identify using the following criteria: (1) density increase of at least a factor of 3 over an L distance of 0.5 Earth's radius (2) density increase larger than 20 cm-3 over an L distance of 0.5 Earth's radius (3) both above criteria should be met for determining the plasmapause crossing. The GUI has shown to be capable of identifying the quiet time plasmapause positions, which is a challenging topic. So far, we have prepared the dataset containing 207 PP. With GUI performance, we estimate that it would be possible to detect much more PP, which is the work in progress. This study is supported by ESA project: "Deducing plasmaspheric wind using CLUSTER satellite" (ESA Contract No: 4000144006/24/NL/EH/yd).

## AS25-0892

# Generation and propagation of field-aligned currents during substorm expansion

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Abrupt intensification of field-aligned currents (FACs) is one of the major characteristics of substorm expansion, but its cause is still a subject of ongoing investigation. Assuming that the FACs are accompanied by Alfvén waves, we traced packets of the Alfvén waves backward in time from the onset position in the ionosphere in global magnetohydrodynamics (MHD) simulation. The Alfvén waves associated with the substorm expansion are found to be generated near the equatorial plane where azimuthally moving plasma works against the magnetic tension force. Importantly, $\mathbf{J}\cdot\mathbf{E}$ is positive in this region, where $\mathbf{J}$ is the current density and $\mathbf{E}$ is the electric field, suggesting that the negative sign of $\mathbf{J}\cdot\mathbf{E}$ does not always imply generation of Alfvén waves. The FACs were generated in the same region due to shear flow and curvature effect. The packets of the Alfvén waves were deflected from the original magnetic field line by ~0.2 hours in MLT in the course of the travel from the equatorial plane to the Earth. This means that they did not travel along the magnetic field line because of the bulk flow of plasma. The azimuthally moving plasma was accelerated by the pressure gradient force directing in the azimuthal direction, which was established by the compression of both plasma pressure and the magnetic field. The compression was caused by the earthward fast flow originating from the near-Earth reconnection. The detailed process from the earthward fast flow of plasma to the intensification of FACs has been clarified by the global MHD simulation.

## AS25-1147

# The Drivers of High-Latitude Scintillations During Storm and Substorm Phases

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In standard GNSS receivers, even mild scintillations can degrade accuracy by several meters while more severe scintillations can lead to total loss of signal lock. We investigate how various ionospheric parameters (such as TEC and particle precipitation) lead to causal responses in Canadian High Arctic Ionospheric Network (CHAIN) amplitude and phase scintillation data (S4 and σφ) over eight years (2013–2021). The analysis shows a significant correlation between the TEC temporal and spatial gradients and the σφ phase scintillation index around dawn and noon magnetic local time and ~70 degrees magnetic latitude with waiting times from zero up to 1 hour. During storms and substorms, the response differs significantly with the strongest response during the storm main phase. The spatial distribution of the response suggests that electron diffuse precipitation may be responsible for dawn-dusk asymmetries, while the response at noon may result from enhanced electron density in the convection throat the develops during storms.

## AS25-1261

# Ionospheric Joule heating and neutral density variations at low Earth orbits during geomagnetic storms

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During geomagnetic storms intense Joule heating causes thermal expansion of the upper atmosphere, thus increasing satellite drag at low Earth orbits (LEO). This chain of events often begin when high-speed stream/stream interaction regions (HSS/SIR) or interplanetary coronal mass ejections (ICME) impact Earth's space environment. In the "Joule heating effects on ionosphere-thermosphere coupling and neutral density (JOIN)" project we determine the statistical distribution of the auroral Joule heating in the northern hemisphere during geomagnetic storms using SuperMAG, SuperDARN and AMPERE data. This is compared with the large-scale atmospheric density variations at LEO observed by the Swarm, GRACE and GRACE-FO satellites.

Based on superposed epoch analysis of 231 geomagnetic storms between 2014 and 2024, it is found that the Joule heating in the ionospheric E-region and neutral density enhancements at LEO show different characteristics depending on the geomagnetic storm driver. The Joule heating has a faster increase at the beginning of the storm main phase when the storm is initiated by a HSS/SIR or sheath region of ICMEs, while a more gradual and longer lasting increase is found in storms driven by magnetic clouds within ICMEs. The thermospheric density enhances gradually during the storm main phase and the enhancements are typically largest (median peak increase of 120%) and longest-lasting for storms driven by MC due to the prolonged interval of intense Joule heating.

## AS25-1315

# Validating an Energy Flux Inversion Method with Satellite Data

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Pulsating aurora is a common and long-lasting type of aurora composed of precipitating electrons with energies up to 100s keV to MeV. Since it is more energetic, it can deposit energy into the D region and below, and accounts for a large amount of energy transferred from the magnetosphere into the ionosphere. To understand the effects of pulsating aurora on the ionosphere/atmosphere we seek to understand its precipitating energy flux spectra. One method to do this is to use an inversion method outlined by Semeter and Kamalabadi [1], that uses an electron density vs altitude profile from an Incoherent Scatter Radar to find the precipitating energy flux. This method uses both an atmospheric chemistry model, that finds the recombination coefficient, and an ionization rate model. In this study we seek to validate a selection of these models by comparing the resulting energy flux to spacecraft data. We use the ELFIN bounce loss cone electron flux during conjunctions with the Poker Flat Incoherent Scatter Radar (PFISR). Since ELFIN's electron energy range is from 50 keV to 5 MeV it overlaps with PFISR's inverted flux range of 1 keV to 500 keV, and as a low earth orbiting spacecraft, its bounce loss cone flux will give the precipitating fluxes. While not a new method, this is the first time this inversion method has been validated with spacecraft data.

## AS25-1385

# The response of the Global Ionosphere Thermosphere Model to reversed two-cell convection produced during a theta aurora event

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The theta aurora, a large-scale auroral emission that forms a bar-like feature across the polar cap connected to both the day- and night-side auroral oval, represents plasma sheet particle energy deposition into the polar ionosphere during periods of northward IMF. The theta aurora dissipates magnetospheric energy into the ionosphere through particle precipitation and Joule heating, which can significantly impact the ionosphere-thermosphere (I-T) system. Typically, I-T global circulation models use empirically-derived quantities to represent magnetospheric driving forces, which can mischaracterize the impacts of magnetospheric events like the theta aurora. However, we use the ionospheric results produced by the Space Weather Modeling Framework (SWMF) simulations of the magnetosphere to run the Global Ionosphere Thermosphere Model (GITM) during a theta aurora event captured by the IMAGE mission on 10-January-1997. We use the real solar wind conditions during the 10-January-1997 theta aurora event to run a high-resolution SWMF MHD simulation coupled with an inner-magnetosphere model. The SWMF simulation results show a reversed two-cell convection pattern in the ionosphere during the interval of the theta aurora observations. We drive GITM with the ionospheric potential, mean energy, and energy flux produced by SWMF to study the impact of reversed two-cell convection on the neutrals, ions, and electrons in the Earth's upper atmosphere. The findings of this study quantify the impact of theta aurora on the I-T system, underscoring the need to account for a broader range of processes in space weather modeling and analysis.

# A21 Advances and challenges of ULF waves in the Earth and planetary magnetospheres

## AS25-0050
## Polarization of ULF waves in non-axisymmetric magnetospheric fields

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Recent satellite observations (e.g. Arase) indicate that the polarization of Ultra Low Frequency (ULF) waves in the terrestrial magnetosphere is often neither poloidal nor toroidal. These observations can be potentially explained by deviation of the background magnetic field from the dipole approximation. We developed a simple example of a non-axisymmetric field which is representative of the magnetospheric field in the dawn or dusk flank. This field is explicitly characterized by a control parameter describing the degree of deviation from the dipole magnetic field. For the proposed magnetic field there is no field-aligned orthogonal coordinate system, therefore shear Alfven waves are described in terms of their covariant components. For this magnetic field, all the metric coefficients can be calculated analytically, thus simplifying the analysis of the wave modes. Our calculations demonstrate that even small deviations of the background magnetic field from axial symmetry result in significant changes in the polarizations of the standing shear Alfven waves. In contrast, the frequencies of the field lines change very slightly. Therefore, our analysis supports the observations of ULF waves of distinctly mixed polarizations in nearly dipole background magnetic fields.

## AS25-0110

# Theoretical and experimental studies of the drift-compressional modes in the Earth's magnetosphere

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A prominent class of the ultra-low-frequency (ULF) waves in the terrestrial magnetosphere is the compressional storm-time Pc5 pulsations observed with satellites and radars. These are the waves with high azimuthal wave numbers m (m>>1) and frequencies usually sufficiently lower than the Alfven frequency on the same field line. The magnetic field oscillations in these waves are accompanied by large plasma pressure modulations in antiphase with the magnetic field. One of the most suitable interpretations of such waves is the drift-compressional mode (DCM). This mode appears in kinetics as the most common compressional mode which requires only finite plasma pressure and plasma inhomogeneity across magnetic shells. This report outlines a theory of DCM as well as recent experimental data confirming the identification of the compressional storm-time Pc5 pulsations with the DCMs. Two generation mechanisms of these modes are considered: by means of the instability caused by bump-on-tail distribution function and strong number density and temperature gradients. Both demand drift resonance with high-energy particles. Yet another important issue is the coupling of the DCM with the Alfven mode due to the plasma inhomogeneity. This coupling can cause a reactive-type plasma instability which can provide another DCM generation mechanism. In this case, the wave-particle drift resonance is not necessary for the instability to develop. Observational evidence for this instability is presented as well. This study was supported by the Russian Science Foundation under Grant No. 25-17-00137.

## AS25-0131

# Recent development in ULF wave research and remaining challenges

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ULF waves continue to be recognized as an integral element of magnetospheric research. This presentation highlights recent studies of the global distribution of waves, wave-particle interaction, and propagation of waves of solar wind origin to the magnetosphere. On the observational side, use of multipoint measurements and statistical analysis of data accumulated in long-lasting spacecraft missions are the key. On the modeling side, use of hybrid codes and advanced global MHD simulations contributed to the improved understanding of the observations. The presentation will also identify remaining challenges and discuss how we can make progress in the near future.

## AS25-0132

# Fundamental poloidal wave activity with a large local time extent

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Fundamental poloidal (P1) waves are a class of ULF waves standing along the background magnetic field. P1 waves are excited in the ring current region and are detected on the ground as giant pulsations (Pgs). In this study, we report a longitudinally extended P1 wave event observed on 24 March 2013 by Van Allen Probes (RBSP, midnight sector), ETS-VIII (morning side), THEMIS-D (dawn sector), and GOES-13 (postnoon sector). At each spacecraft, the magnetic field perturbations exhibit a strong radial component and a finite compressional component consistent with previously reported P1 waves. The standing wave harmonic mode is determined either from the phase relationship between the radial component of the magnetic field and the azimuthal component of the electric field (RBSP and THEMIS-D) or from the frequency relationship between the poloidal wave and the simultaneously detected multiharmonic toroidal waves (ETS-VIII and GOES-13). A Pg pulsation was detected at the Gillam station near the magnetic field footprint of GOES-13. From the wave phase delay between RBSP-A and -B we are able to determine the azimuthal wave number (m) at midnight to be -50 (for westward propagation). This m value means a strong ionospheric attenuation of the waves and explains why few Pg events have been reported near midnight. The observations suggest that P1 waves often occupy a large local time domain but Pgs are limited in local time due to the screening effect.

## AS25-0265

# ULF Modulations on Plasma Environment and Coherent Waves of Mercury's Magnetosphere: MESSENGER's Observation

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Ultra low frequency (ULF) waves are fundamental waves that can energize, transport, and scatter charged particles in planetary magnetospheres. With the measurements from MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER), we investigate the proton flux fluctuations and coherent waves associated with a series of ULF waves on the flanks of Mercury's magnetosphere. The ULF waves are mainly compressional with a frequency of ~15 mHz and significantly modulate the intensity of proton flux. The coherent waves accompanied by the ULF waves correspond to a higher frequency (~1 Hz). The wave power and compressibility of the coherent waves vary quasi-periodically with the ~15 mHz ULF waves. We conclude that the compressional ULF waves modulate the coherent waves with higher frequency. This modulation might result from the associated periodic proton flux changes and helps us understand the nature of the ~1 Hz waves better

## AS25-0314

# Disturbances in ULF range recorded by ground-based magnetometers at mid latitudes during the storm time May 10–13, 2024

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The objective of this work is to find the spectral characteristics of the geomagnetic ULF disturbances in the Pc3–5 range (10–600 s), examine their propagation specifics and analyze their relations with solar wind parameters during the storm time May 10–13, 2024. The multipoint observatory geomagnetic data recorded at 1 s time-resolution by fluxgate and induction magnetometers located at mid latitudes (40.957–47.930 N) in EBR (Spain), WIC (Austria), NCK (Hungary)-fluxgate instruments (www.intermagnet.org), and PAG (Bulgaria)-induction instrument. The wavelet coherence—a measure of the correlation between two signals in the time-frequency plane—is obtained for a wide range of frequencies. The phase differences between every two observatories were examined. The largest phase shift compared to the other stations is observed at the PAG observatory. It varies in the range (0-π/2) for the different frequency ranges with the largest being between EBR and PAG. The values of coherence between each pair of observatories vary in the time-frequency plane. The weakest correlations are observed between EBR and the other three stations, which is most likely related to the latitudinal variation of Pc3–Pc5, considering that EBR is the southernmost observatory. The spectral analysis and FFT bandpass filters point out that the disturbances in the range of 10–150s recorded at EBR observatory significantly differ from the other observatories in terms of their amplitudes and waveform, while disturbances in the Pc5 range (150–600s) exhibit the same spatial and spectral characteristics for all observatories.

## AS25-0370

# Comprehensive review of ULF waves at set of discrete frequencies

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The almost simultaneous occurrence of Earth's magnetospheric ULF waves at a set of different frequencies in the range f ≈ 1–5 mHz (T ≈ 200–1000 s, overlapping the range of Pc5 ULF waves) has been frequently reported and discussed in the last 35 years. The first observations of ULF waves with an apparently stable set of favorite frequencies, namely, f ≈ 1.3, ≈ 1.9, ≈ 2.6–2.7, and ≈ 3.2–3.4 mHz, sparked the interest of the community who often referred to them as CM- (from Cavity Mode) or "magic" frequencies. However, our comprehensive review of the literature results, including ionospheric, geomagnetic, and magnetospheric observations, shows the absence of a stable and persistent absolute set of favorite frequencies. Rather, the collective analysis of results from investigations over the last three decades reveals a strong predominance of ULF waves at frequencies between f ≈ 1.5–2.5 mHz, with percentages maximizing at f ≈ 1.9 mHz and rapidly decreasing with increasing frequency. Interestingly, we found that periodic solar wind density disturbances can very well serve a direct or indirect driver of magnetospheric fluctuations centered around f ≈ 1.9 mHz. Finally, by revisiting these historical observations, we argue that an eventual occurrence of ULF waves at an absolute favorite set of frequencies could be obscured by: (i) the low occurrence rate of related mechanisms with respect to others generating waves over a continuum or (ii) the comparable occurrence rates between mechanisms generating waves at complementary sets of discrete frequencies.

## AS25-0428

# Detection and characteristics of quarter-wave modes through simultaneous observations in the magnetosphere, ionosphere, and ground

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We investigate the characteristics of quarter-wave modes in ultra-low frequency (ULF) waves using simultaneous observations in the magnetosphere, ionosphere, and ground. This analysis was made for a special period during the campaign observations with the Arase satellite and the SuperDARN radars, providing a rare opportunity to observe quarter-wave modes in both regions. From 00:00 to 04:00 UT on 23rd November 2022, the SuperDARN radars in Canada (Prince George and Saskatoon) observed ULF waves in the Pc5 frequency range in the subauroral dusk-side ionosphere. The Range-Time-Intensity (RTI) plot exhibited a characteristic caterpillar-like pattern with periodic oscillations in the line-of-sight Doppler velocity. The Arase satellite's magnetic footprint was within the radar's field of view, and several CARISMA ground magnetometers were situated nearby, enabling multi-point observations. Ground magnetometer data indicated a field line resonance (FLR) at magnetic latitude ~68°. Based on previous studies, a transition from a half-wave to a quarter-wave mode occurs when the ionospheric conductance ratio exceeds 5. This event met that condition, with a ratio between 6.7 and 10.3. The electron density estimated from Arase's PWE/HFA data supported the expected FLR frequency of the quarter-wave mode. Analysis of electric and magnetic field data from Arase indicated that this wave exhibited toroidal mode characteristics, with Poynting flux flowing along magnetic field lines toward the northern hemisphere (night side). This presentation will discuss how ionospheric conductance asymmetry influences the excitation of quarter-wave modes and analyze the relationship between wave energy propagation and dissipation along field lines.

## AS25-0430

# Longitudinal Characteristics of Long Duration Pc1 Signatures Observed from Southern Auroral Latitudes

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We report signatures of long duration (approximately 12 hours long) Pc1 events using longitudinally distributed geomagnetic stations on 24 Jan 2018 at southern auroral latitudes. The event is initiated by a very gradual compression of magnetosphere that lasted for more than 10 hours. During this time, MMS satellite orbited near the dayside magnetopause, which indicated the influence of dynamic pressure as compressions of the magnetopause. The magnetic signatures supported the observations with inward and outward motion of the magnetopause. Detailed analysis of the event indicated that there are two parts of the event with the initial part of the event driven under the influence of the dynamic pressure, however the signature in the night side signature seemed to be driven by auroral activity. The counter signature of the Pc1 event is also observed in the northern hemisphere from Finnish chain of stations.

## AS25-0533

# Spatial structure of compressional ULF waves in the topside ionosphere

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**Abstract:**

In this paper, we present results of a statistical study of Pc3 and Pi2 compressional waves observed at low-Earth orbit (LEO) by the Swarm satellites. We place particular emphasis on investigating the distribution of wave coherence and phase difference as functions of magnetic latitude and local time. This study extends previous work [1] utilising over 10 years of Swarm observations. By leveraging the multipoint observations from Swarm, we reconstructed the spatial structure – coherence, amplitude and phase relations – of these wave types. This technique could pave the way for investigating how the spatial structures respond to variations in the interplanetary and Geospace environment. For example, we aim to explore how wave amplitudes and spatial extents change in response to varying solar wind forcing, as well as how the spatial extent of cavity mode Pi2 waves reacts to changes in plasmasphere size.

[1] Heilig, B., and P. R. Sutcliffe (2016), Coherence and phase structure of compressional ULF waves at low-Earth orbit observed by the Swarm satellites, *Geophys. Res. Lett.*, 43, 945–951, doi:10.1002/2015GL067199.

## AS25-0670

# Subduction Zone Micro-Fracturing and Magnetic Field Variations: A Case Study of the Tapaktuan M6.2 Earthquake on January 31, 2025

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Tapaktuan, one of the cities in South Aceh, Aceh Province, is part of the complex geological zone of Sumatra due to its proximity to the subduction zone between the Indo-Australian Plate and the Eurasian Plate, as well as its influence from the Sumatran Fault (Great Sumatran Fault). On January 31, 2025, an earthquake with a significant magnitude of M6.2 occurred in Tapaktuan, with an intensity scale of IV MMI. This research aims to analyze changes in the magnetic field prior to this earthquake, validated by the Dst index to eliminate anomalies from external sources. The data used in this study comes from the Magnetic Data Acquisition System (MAGDAS) SMG located in Samosir. The polarization of the Z/H component indicates a significant magnetic anomaly in the frequency range of 0.012–0.022 Hz, resulting from micro-fracturing along the subduction zone south of Sumatra Island. By observing the direction of the anomaly's emergence using the single station transfer function method, several anomalies were detected, validating the increase in rock stress that caused geo-electrical changes propagating through the lithosphere. The maximum amplitude of the polarization ratio was 12.717, with this anomaly peaking just before the earthquake and pointing toward the earthquake area, with a potential magnitude of approximately ±6.1 M.

## AS25-0791

# GPS Observations of Rapid Acceleration Bursts in the Van Allen Radiation Belt

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Geomagnetic storms may cause rapid changes in Earth's Van Allen radiation belt content, but standard satellite missions often fail to capture acceleration events occurring over short timescales due to orbital limitations. To address this in this study, we utilized energetic electron measurements from the GPS satellite constellation to analyze a very fast acceleration event during the geomagnetic storm of August 26, 2018.

Our analysis reveals two distinct electron acceleration bursts, each governed by different mechanisms. The initial burst lasted approximately 80 minutes and increased electron phase space density (PSD) by nearly four orders of magnitude, consistent with inward radial diffusion driven by ULF waves. This acceleration phase exhibited clear positive PSD gradients, indicative of inward radial diffusion, supported by elevated ULF wave power detected by ground-based magnetometers. The distinct second burst, significantly shorter (~20 minutes), elevated electron PSD by only an order of magnitude. This burst featured peaked PSD profiles and coincided with enhanced chorus wave activity observed by the Arase satellite, suggesting local acceleration through wave-particle interactions as the dominant process.

Our study demonstrates the critical advantage of GPS constellation data for resolving fast electron acceleration processes within the radiation belts. By providing near-continuous coverage, GPS measurements have revealed that distinct physical mechanisms—ULF-wave radial diffusion and local chorus wave acceleration—can operate sequentially, enhancing radiation belt populations over intervals as short as minutes to hours. This underscores the value of multi-point and constellation-based measurements for advancing radiation belt science.

## AS25-0795

# Bounce-resonant wave-particle interaction in Jupiter's magnetosphere

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Standing Alfven waves in Jupiter's magnetosphere have eigenperiods on the order of tens to hundreds of minutes that are similar to bounce periods of sub-keV plasma particles. Directly sampling Alfvenic magnetic perturbations at such long periods using a fast-moving spacecraft is challenging. Recent observations made by the JADE plasma instrument onboard the Juno spacecraft have shown the presence of energy distributions that appear banded, with alternative enhancements and depletions. Bands have been observed at energies that are linearly separated in speed, thereby suggesting the influence of a wave-particle resonance process that interacts with the bounce motion of a particle. Banded distributions of electrons and protons have been observed in magnetic flux tubes connected to the wakes of the Galilean moons. In addition, banded distributions have also been observed for lower energy H+, O+ or S++, O++, S+++ ions simultaneously, with bounce periods of these ions matching harmonics of Jupiter's corotation frequency. These observations, which are observed consistently, illustrate the importance of bounce resonance in Jupiter's magnetosphere. The observations also illustrate the utility of using particle observations in the closed field line region to infer wave modulations when the electromagnetic field cannot be measured directly due to sampling constraints.

## AS25-0983

# EMIC Wave Propagation in the Dayside Magnetosphere: A Comparison of Full-Wave Simulations and Observations

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We explore the characteristics of EMIC waves generated in a non-dipole, compressed magnetic field at the minimum of the magnetic field. We conducted 2D full-wave simulations using the Petra-M code, focusing on a compressed magnetic field in the outer dayside magnetosphere for a range of L values (L=8–10). By comparing the simulation results with MMS observations, we aim to understand how the observed wave characteristics are affected by a shifting source region across different L-shells. Our findings [1] indicate that the direction of the Poynting vector systematically changes depending on the local source location of the wave, which is consistent with the observations [2]. EMIC waves propagate along the magnetic field line and reach both the northern and southern hemispheres; however, there is a notable difference in the power of EMIC waves between the two hemispheres, indicating seasonal asymmetries in their occurrence. We also found that left-handed polarization is dominant near the source location in the outer magnetosphere, while linear polarization is more prevalent near Earth. This observation is in excellent agreement with previous findings from the Cluster mission [3].

[1] Kim, E.-H. et al. (2025) Geophy. Res. Lett, 52, e2024GL113368.
[2] Vines, S. K. et al. (2019) Geophy. Res. Lett, 46 (11), 5707–5716.
[3] Allen, R. C. et al. (2015) J. Geophys. Res. Space Phys., 120, doi: 10.1002/2015JA021333.

## AS25-0987

# Experiment FENICS-2024: Excitation of artificial Pc1 pulsations

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In July-August 2024, the active experiment FENICS-2024 was conducted on the Kola Peninsula to generate artificial electromagnetic signals using two power transmission lines as a horizontal radiating antenna. The generator frequency and current varied from session to session during nighttime. The paper presents the results of ultra-low-frequency signal registration at magnetic stations located up to ~2100 km from the transmission line. Signals with frequencies from 1 Hz to 9 Hz with normalized amplitudes from ~0.3 fT/A to ~0.8 fT/A were recorded. For theoretical interpretation of the experiment results, a numerical model of the ULF field in the atmosphere and ionosphere generated by the horizontal surface current was used. The model is based on solving the system of Maxwell's equations in a vertically inhomogeneous atmosphere and ionosphere. In particular, this model correctly considers the contribution of ionospheric waveguide propagation channel. Numerical calculations are also compared with approximate analytical estimates. The calculations turned out to be in a qualitative agreement with the observations. The observational results supported by numerical modeling have shown the potential of a new type of active experiments for ULF signal generation for large-scale magnetotelluric sounding and for the modification of near-Earth plasma with artificial signals.

## AS25-1091

# Theory and modeling of large scale plasmapause surface waves

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The plasmapause in Earth's magnetosphere represents the boundary between the plasma which co-rotates with the Earth (plasmasphere), and the more tenuous plasmatrough outside. The density change across the plasmapause can be large, changing by approximately 1–2 orders of magnitude depending on the prevailing conditions. This would suggest it to be a location where magnetohydrodynamic (MHD) surface waves can form, and indeed, this has been proposed in previous works to explain ultra-low frequency (ULF) wave observations around the plasmapause location. The main question is how such a large scale surface wave on the plasmapause would be excited. In this work, we propose a model whereby surface waves at the plasmapause are driven by energy input from the magnetopause through solar wind driving. We derive an analytical form for the amplitude of these modes with this new driven boundary condition at the magnetopause. The excitation of these waves is then tested in several MHD simulations, where the model geometry, wavenumbers and temporal dependence of the magnetopause driver are varied. We establish that surface waves on the plasmapause can be excited by driving from the magnetopause, and that this still occurs with impulsive and continuous broadband driving. The azimuthal scale of the wave is a critical factor for this excitation, with longer azimuthal scales more favorable for driving larger amplitude surface waves. This mechanism provides new insight for how large scale and large amplitude ULF waves can access the inner magnetosphere, with potential implications for their interaction with radiation belt particles.

## AS25-1149

# Arase satellite observation of toroidal Pc 5 waves extending to low L-shells during the May 2024 geomagnetic storm

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Cold heavy ions play an important role in magnetospheric dynamics in various ways: they decrease the Alfvén speed, leading to a longer time constant for processes related to this speed. Moreover, the composition of cold ions affects the dispersion relation of plasma waves, affecting wave-particle interactions. However, the dynamics of cold heavy ions are not yet fully understood due to limited direct measurements. To reveal the ion composition and its variations during intense geomagnetic storms, this study conducts a magnetoseismic analysis of Pc 5 waves observed by the Arase satellite during the May 2024 geomagnetic storm. Standing Alfvén toroidal Pc 5 waves were detected in the early recovery phase at L = 2.5–5.2. The estimated value of the average ion mass increases up to 20 near the Earth. This unrealistic value is likely caused by the inaccuracy of the density and magnetic field models used in the estimation. Using a power-law index of $\alpha = -4$ in the density model reduces the average ion mass to approximately 10, although $\alpha = -4$ is also unrealistic. While we found that the magnetic field at Arase (MLAT > 20°) are similar to the model field, it remains possible that the magnetic field is weakened by ring current ions confined around the magnetic equator, resulting in longer wave periods due to low Alfvén speed. We conclude that the low frequency of the standing Alfvén waves arises from the combination of cold heavy ions and ring current ions during the intense storm.

## A22 Magnetospheric boundary layers in the dayside and beyond

### AS25-0053

# Transport of Mantle Plasma Across the Plasma Sheet High-Latitude Boundary

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The plasma sheet high-latitude boundary (PSHB) is the boundary separating the magnetotail plasma sheet in the closed field-ling region and the lobe/mantle in the open field-line region. The transport of the mantle plasma in the lobe to the PSHB and the subsequent crossing of the PSHB is one of the major plasma sources for the plasma sheet. In the first part of my talk, I will present MMS and ARTEMIS observations and global hybrid simulations to show our understanding of the appearance of the mantle plasma just outside the PSHB and the dependence on the IMF direction. For the second part of the talk, I will present MMS observations to demonstrate the diffusive transport by kinetic Alfven waves as one of the mechanisms for the plasma transport across the PSHB.

## AS25-0088

# Particle precipitation and field-aligned electric field at the dayside boundary layer and cusp

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An open-field line particle precipitation model for low latitude boundary layer (LLB), cusp, mantle, and polar rain compare was developed. Electrons have higher thermal speeds than ions and can enter the magnetosphere in greater quantities. As a result, a retarding field-aligned potential drop develops in order to limit the electron entries to maintain charge-quasi neutrality. In the model, the potential drops are small in the cusp, intermediate in the mantle, and high in the polar rain and open-field LLBL. The model potential drops compare well with those obtained from the fits of the DMSP electron spectra. The polar rain potential drop is further checked by comparing the phase space densities of the DMSP electrons with those of the solar wind suptrathermal (strahl) electrons. The model potential drop in the polar rain agrees qualitatively with the observations, but near the open-closed boundary at dusk, the polar rain electrons appear to have gone through accelerating potential drop. At the dusk flank of the magnetopause boundary, the velocity shear between the solar wind and magnetospheric plasma can generate an upward field-aligned (region-1) current. When the electron density at the boundary layer is too low to provide enough electron current carriers, a potential drop develops to draw more electrons downward. The open-field line particle precipitation model does not take these processes into account. However, a boundary layer model that takes into account these processes was developed. The potential drops from the boundary layer model compare well with those from the DMSP observations.

## AS25-0137

# Oxygen ion escape associated with three-dimensional Kelvin-Helmholtz instability at Venusian magnetospheric boundary layer

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How oxygens escape from Venus has long been a fundamental but controversial topic in the planetary research. Among various key mechanisms, the Kelvin-Helmholtz instability (KHI) has been suggested to play an important role in the oxygen ion escape from Venus. Limited by either scarce in-situ observations or simplified theoretical estimations, the mystery of oxygen ion escape process associated with KHI is still unsettled. Here we present the first three-dimensional configuration of KHI at Venus with a global multi-fluid magnetohydrodynamics model, showing a significantly fine structure and evolution of the KHI. KHI mainly occurred at the low latitude boundary layer if defining the interplanetary magnetic field-perpendicular plane as the equatorial plane, resulting in escaping oxygen ions through mixing with the solar wind at the Venusian boundary layer, with an escape rate around $4\times10^{24}$ $s^{-1}$. The results provide new insights into the basic physical process of atmospheric loss at other unmagnetized planet.

## AS25-0175

# Planetary impacts of foreshock magnetic fluctuations from quasi-parallel bow shocks

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Upstream of quasi-parallel bow shocks, reflected ions generate ion-ion instabilities, which result in magnetic fluctuations that can advect through the shock and interact with planetary magnetospheres. The most intense of such structures can drive local magnetopause reconnection where there would otherwise have been no magnetic shear. With increasing heliocentric distance, the solar wind Mach number (M_A, the ratio of solar wind velocity to the local Alfven speed) generally increases, such that planets further from the sun have typically stronger shocks. Additionally, the interplanetary magnetic field is more often quasi-radial closer to the sun, leading to greater likelihood of a quasi-parallel bow shock at the inner planets (especially in the region directly upstream of the planet). Using the solar system as a natural laboratory, we have compiled ion foreshock events upstream of the quasi-parallel bow shock at the planets Mercury, Earth, Mars, Jupiter, and Saturn. A linear scaling between maximum magnetic fluctuation amplitude and M_A is calculated, although the time dependent nature of the foreshock produces a wide spread in the data. Furthermore, we find that based on the dominant fluctuation frequency for the largest amplitude events at each planet, Mars exists in a special regime where the wave period of the magnetic fluctuations can be similar to or longer than the global magnetospheric convection timescale.

## AS25-0250

# On the Growth and Development of Non-Linear Kelvin–Helmholtz Instability along Mars' Boundary Layer

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Without a global intrinsic magnetic field but a localized crustal magnetic field, Mars' space environment interacts directly with the solar wind to form a unique induced hybrid magnetosphere. The well-defined plasma boundary layer separating the solar wind and martian plasma environment, also known as the induced magnetosphere boundary (IMB), had been observed and studied by earlier missions to Mars. The direct interaction of the solar wind with the martian induced magnetosphere results in a velocity shear along the IMB where Kelvin-Helmoltz instability (KHI) was thought to potentially develop along this boundary. Earlier numerical simulations did not provide a clear answer on whether KHI can occur at Mars. However, recent observations from the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission provide more definitive evidence that KH vortices (and hence non-linear development of KHI) can occur at Mars. In this presentation, we will provide a summary of our current state of understanding of KH instability at Mars, and present the latest multi-case studies analysis of additional observations of KH events at Mars. We will also discuss the implications of the formation of KH vortices at Mars, with regards to the particle energization within the mixing region of the KH vortex structure via magnetic reconnection, secondary instabilities or other turbulent processes, and atmospheric ion escape flux due to the detachment of plasma clouds during the late nonlinear stage of KH instability.

## AS25-0393

# Is it possible to identify open magnetic flux in the giant magnetospheres?

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Numerical simulations have shown that Jupiter's magnetosphere has a very different magnetic field topology compared with the familiar terrestrial magnetosphere [Zhang et al., 2021]. The simulated open flux region is confined to the crescent region, bounded by the closed flux in the lower and higher latitude regions. On the dawn flank, the open flux region can exhibit anti-corotational flows, consistent with solar wind flow [Delamere et al., 2024]. However, the open flux is highly variable, so it is possible that open (closed) field lines, created through intermittent reconnection, can also exhibit corotational (anti-corotational) flows and contain magnetospheric (solar wind) plasma. Numerical simulations can determine, via field line tracing, whether fields are open or closed (a consideration that is almost intractable from observational analysis alone). Therefore, a promising method to identify open flux signatures in Juno data, is through a careful data/model comparison approach. With this motivation in mind, we will discuss properties (e.g., KH stability, magnetic reconnection) of the mid-mid-latitude open/closed boundaries in the GAMERA simulations and the implications for the transport of mass, momentum, energy, and magnetic flux. We will also review the results from test particle simulations, identifying properties of particles on open field lines for further data comparison. We will trace fluid elements near the open/closed boundary to investigate intermittent reconnection processes and the associated momentum transfer timescales relevant to azimuthal flow. Finally, simulated parallel currents and Alfvenic Poynting flux at the ionospheric boundary will be used as proxies for auroral emissions for comparison with auroral observations.

## AS25-0416

# Auroral Beads Powered by Kelvin-Helmholtz Vortices at the Magnetopause Boundary Layer

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Sheared flows at the magnetopause boundary layer or plasma sheet can drive field-aligned currents and power auroral precipitation. As the sheared layers become unstable, vortices can develop leading to auroral bead formation. We utilize a quasi-static model to determine how the field-aligned current structure depends on ionospheric and boundary layer parameters. A new feature of this model is a self-consistent treatment of the precipitating electrons, which contribute to the ionospheric conductivity. One of the features of this model is the discovery of an optimum scale that maximizes electron precipitation, and we show how this scale depends on the vortex properties and the level of photoionization. We show examples and statistics of dayside auroral beads detected by DMSP at times when Kelvin-Helmholtz vortices are detected by Themis or MMS, and discuss how observed dawn-dusk asymmetries are consistent with the model.

## AS25-0666

# Direct Observations of Energy Transfer from Resonant Electrons to Whistler-mode Waves in Magnetosheath of Earth

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This study shows an observation of electrons with nongyrotropic distributions around the cyclotron resonance velocity as the direct evidence of locally ongoing nonlinear wave-particle interaction between the electrons and whistler-mode waves near dayside magnetopause reconnection. The nonlinear wave-particle interaction theory for coherent large amplitude waves predicts that electrons around the cyclotron resonance velocity exhibit nongyrotropy due to the phase trapping motion in the presence of an appropriate magnitude of spatial gradient of magnetic field intensity and/or temporal variation of the wave frequency. The electrons with a nongyrotropic distribution are expected to exchange energy and momentum with these waves effectively. In this presentation, we show observational results of electron distributions with ultra-high temporal resolution data obtained by the Magnetospheric Multiscale spacecraft during a whistler-mode wave event around the magnetosheath-side separatrix of the dayside magnetopause reconnection. We identified electron flux hole events that induce wave growth; a hole at an appropriate relative phase angle to the whistler-mode wave magnetic field appeared only close to the cyclotron resonance velocity. During the time interval, the magnitude of the gradient of magnetic field intensity along the magnetic field line, which is derived by multipoint measurements, is consistent with an appropriate magnitude to cause phase trapping of resonant electrons. These results provide direct evidence of locally ongoing nonlinear wave-particle interaction between whistler-mode waves and electrons due to phase trapping.

## AS25-0731

# High-speed magnetosheath jets and their soft X-ray imaging through numerical simulations

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The high-speed magnetosheath jets are finite-sized plasma irregularities with an excess of density and velocity with respect to the background magnetosheath that are propagating in the anti-sunward direction and impact the magnetopause, generating local and global effects on the magnetic and plasma environment of our planet. The dynamics of jets while interacting with the magnetopause and their transport from the magnetosheath to the magnetosphere continues to represent an active research topic in the field of solar-terrestrial physics. The upcoming Solar wind-Magnetosphere-Ionosphere Link Explorer (SMILE) mission provides a great opportunity to observe in soft X-rays the solar wind interaction with the Earth's magnetic field. The soft X-rays are emitted through the solar wind charge exchange process and the resulting photons are detected by the Soft X-ray Imager (SXI) on-board SMILE. In this paper we present our latest results on the numerical simulation of soft X-ray imaging of high-speed magnetosheath jets that are moving in the vicinity of the terrestrial magnetopause. We performed a parametric study on the soft X-ray visibility of jets in the magnetosheath and magnetosphere by varying their number density and bulk velocity. In this way we evaluate the jet's observability potential by SMILE-SXI.

## AS25-1014

# Dawn-Dusk Asymmetry of Kelvin-Helmholtz Vortices along Kronian Magnetopause

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The Kelvin-Helmholtz instability (KHI) vortex at Saturn's magnetopause, driven by the interaction between Saturn's magnetosphere and the solar wind, represent a significant process. Observational evidence confirms the existence of these KHI structures at Saturn's magnetopause. With rapid rotation, Saturn is expected to exhibit dawn-dusk asymmetry in KHI characteristics or spatial distribution. Statistical analyses of Cassini mission data have yielded conflicting results, with some studies indicating more KHI features on the duskside and others on the dawnside. To investigate the dawn-dusk asymmetry of Saturn's KHI, we conducted global three-dimensional magnetohydrodynamic simulations of Saturn's magnetosphere. We found that KHI structures continuously develop in the prenoon sector of Saturn's magnetosphere and propagate towards both the dawn and dusk sides, exhibiting clear dawn-dusk asymmetry in their growth and propagation. At a fixed eigenfrequency, KHI structures propagate more stably towards the duskside with higher eigenfrequencies. Conversely, on the dawnside, KHI structures exhibit lower eigenfrequencies and unstable growth and propagation due to the presence of more complex physical processes. Our work elucidates the characteristics of KHI at Saturn's magnetopause, which is important for understanding the interaction between rotation-driven planetary magnetosphere and solar wind.

## AS25-1344

# Recent Advancements in Kelvin-Helmholtz Instability Occurring in Earth's Magnetopause Compared to Magnetic Reconnection

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Earth's magnetopause is characterized by the existence of magnetic field shear that drives magnetic reconnection, velocity shear that triggers the Kelvin-Helmholtz instability, as well as density and temperature gradients, between the hot and tenuous magnetosphere and cold and dense magnetosheath, which seed interchange instability. Among these physical processes, two key mechanisms governing the Sun-Earth interaction are thought to be magnetic reconnection (RX) and the Kelvin-Helmholtz instability (KHI). Recent high-time resolution observations and start-of-the-art simulations revealed that KHI can lead to the onset of RX and vice versa. This highlights the close linkage between KHI and RX, the effects of which can propagate to the entire global system. This presentation focuses on recent advancements in understanding the similarities and differences between RX and KHI occurring on Earth's magnetopause. The former includes the multi-scale nature exhibited by both processes, while the latter emphasizes the intrinsic differences in their scalability. Another key difference lies in their global effects. While the roles and impacts of RX is well-established, those of KHI are less highlighted. In this context, we provide in-situ evidence of the global effects of KHI through a unique observation from the Magnetospheric Multiscale (MMS) mission in its string-of-pearls configuration. This talk concludes with brief suggestions of a mission concept optimized for magnetopause KHI, a less-explored area in Heliophysics research.

## AS25-1383

# Magnetospheric boundary layers in the dayside and beyond

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The magnetospheric boundary layers are formed where the solar wind meets the Earth's magnetosphere. First, at the planetary bow shocks the solar wind flow slows down, heating and compressing the plasma, forming a turbulent sheath region around the Earth, the magnetosheath. The boundary between the magnetosheath and the Earth's magnetosphere often is not a simple tangential discontinuity, but its properties depend on the past solar wind, interplanetary magnetic and magnetospheric history. The low -latitude boundary layer is often on both closed and open field lines, consisting of mixture of plasma at different energies, temperatures and densities. During the northward IMF, the double high-latitude reconnection, Kelvin-Helmholtz instability and associated secondary processes effectively bring cold and dense solar wind plasma into the magnetosphere, contributing to boundary layer formation. During southward IMF, the dayside boundaries are typically thinner due to enhanced reconnection which brings the magnetic flux over the polar cap into the magnetotail. During encounters of the Coronal Mass Ejections, the magnetosphere is strongly driven, leading to complex properties of the boundary layers, in particular during the intervals of sub-Alfvenic flows. The dayside, high-latitude boundary layer properties are strongly driven by reconnection in the vicinity of the high-altitude cusps, which can lead to formation of diamagnetic cavities and populations of trapped energetic particles. In this talk we review the status of dayside boundary layers focusing on Earth and comparing with some observations at other planets.

# A23 Radiation Belt Dynamics, Effects of Wave Activity, and the Role of the Cold Plasma Background

## AS25-0044

## Spatial and pitch angle distributions of low-energy (<300 eV) O+ plasma in the inner magnetosphere

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In the magnetosphere, the ion composition of background plasma is a critical parameter that significantly influences various in situ electromagnetic phenomena, including solar wind–magnetosphere coupling, magnetic reconnection, the Kelvin-Helmholtz instability, electromagnetic ion cyclotron waves, and magnetohydrodynamic waves. In particular, $O^+$ ions, which have 16 times the mass of $H^+$ ions, strongly affect the mass density of the background plasma. Therefore, it is essential to investigate when, where, and how their low-energy flux varies.

In this study, we investigate the inner magnetosphere, using data from the Arase satellite collected over approximately 6.3 years. A statistical analysis of 50–300 eV $O^+$ ion flux measured by the LEP-i instrument onboard Arase revealed the following key findings: (1) the peak of the $O^+$ ion flux is frequently observed near the plasmasphere boundary, (2) the mean $O^+$ ion flux is significantly high in the region L = 3–5, 21–12 MLT, (3) as magnetic disturbance increases, the overall $O^+$ flux also increases; however, the flux at L = 6 remains unchanged, and (4) the pitch angle distribution of the $O^+$ flux exhibits a cigar-type shape, indicating a strong field-aligned component. These statistical observations of low-energy $O^+$ plasma are in good agreement with the expected evolution of field-aligned low-energy $O^+$ (FALEO) ions, which are believed to flow out from the ionosphere into the inner magnetosphere during substorms and move along magnetic field lines. This suggests that FALEO is the primary source of low-energy $O^+$ plasma with energies below 300 eV.

## AS25-0130

# Investigating the Role of Lightning-Generated Whistlers in Plasmaspheric Hiss Formation and Radiation Belt Dynamics

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Plasmaspheric hiss (PH) plays a key role in radiation belt dynamics by driving electron loss and shaping belt structures. While several sources of PH have been proposed, the contribution of lightning-generated whistlers relative to chorus waves and local wave growth remains uncertain. This study utilizes global lightning observations from the World Wide Lightning Location Network (WWLLN) along with high-resolution wave and particle data from NASA's Van Allen Probes (RBSP) and THEMIS missions to examine the connection between lightning activity and PH occurrence. By correlating PH events with global lightning activity, we aim to quantify the contribution of lightning-generated whistlers to PH and assess their influence on wave-particle interactions. The findings will improve our understanding of PH generation and its role in radiation belt dynamics.

## AS25-0343

# Quasiperiodic emissions: Evidence for wave bouncing and understanding the modulation period

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Quasiperiodic (QP) emissions are whistler-mode electromagnetic waves with frequencies of a few kHz observed in the Earth's inner magnetosphere, whose intensity is nearly periodically modulated with modulation periods ranging from tens of seconds to minutes. Energetic particle precipitation related to these events is demonstrated. We further analyze detailed properties of a large number of these events observed by the DEMETER spacecraft at low altitudes and by the Van Allen Probes spacecraft in the equatorial region at larger radial distances. We show evidence of the waves bouncing between the hemispheres, resulting in a fine inner structure corresponding to bouncing wave elements. We investigate the wave modulation periods in relation to calculated whistler hop times and in-situ measured plasma and energetic particle properties. Event occurrence and characteristics at low altitudes, in the plasmasphere, and in the plasma trough are systematically compared. Finally, the QP wave intensity and propagation are contrasted with hiss emissions occurring for some events simultaneously at lower frequencies.

## AS25-0347

# Detection and statistical analysis of lightning whistlers in the DEMETER satellite data

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Lightning-generated whistlers play a significant role in the Earth's magnetosphere. For example, they are one of the electron precipitation drivers. In this study, we focus on the automated detection of lightning whistlers in the satellite wave data and their statistical properties. We use the burst mode data acquired by the electric field instrument onboard the French micro-satellite DEMETER. We train a YOLOv11-m object detection model to recognize whistler traces in spectrograms of power spectral density of electric field fluctuations using a manually labeled training dataset consisting of about 600 images, which contain about 6000 whistlers. We estimate relevant whistler parameters, especially the whistler dispersion. In the statistical analysis part, we focus on the comparison of our results with the data provided by the neural network for whistler detection onboard the DEMETER satellite. The temporal and spatial distributions of whistlers and their parameters are determined and compared with the global lightning activity.

## AS25-0376

# Observations of power line harmonic radiation and the ZEVS transmitter signal by a ground-based station and spacecraft

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We study the properties of Power Line Harmonic Radiation (PLHR), a type of electromagnetic emission generated by power systems on the ground, in relation to geomagnetic activity. Specifically, we investigate how geomagnetically induced currents (GICs) – generated by sudden magnetic field changes during space weather events and flowing through power grids – influence the generation and intensity of PLHR. For this purpose, we use high-resolution wave data from the ground-based Kannuslehto station in northern Finland, complemented by measurements from the low-altitude DEMETER spacecraft. Magnetic field variations, determined using magnetometer measurements near the Kannuslehto station, serve as a proxy for GIC strength. We show that during geomagnetically disturbed periods with significantly increased GIC levels, PLHR intensities are enhanced, primarily at even harmonics. Additionally, we examine the intensity of the 82 Hz signal generated by the Russian ZEVS military transmitter. Given its frequency similarity to PLHR, this signal allows us to estimate characteristic spatial scales related to propagation, extending to approximately 1000 km.

## AS25-0470

# Statistical characteristics and propagation of high latitude VLF bursty-patches from multi-point observations in Finland

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Extremely Low and Very Low Frequency ELF/VLF waves (0.3–30 kHz) play a key role in radiation belt dynamics by influencing energetic electron behavior through particle acceleration and losses by pitch angle scattering. Understanding their magnetospheric and ionospheric propagation is crucial for modeling particle populations. The PWING network, expanded in 2022 with a VLF receiver in Oulujarvi (OUJ, MLAT = 61.3° N, L = 4.4) and in 2024 with another one in Angeli (ANG, MLAT = 65.8° N, L = 6.2), Finland. Combined with the SGO Kannuslehto station (KAN, 64.4° N, L = 5.4) we hoped for the first continuous latitudinal chain of VLF receivers enabling statistical and long-term studies of wave occurrence and latitudinal propagation. Unfortunately, before ANG came into operation, KAN was destroyed by a lightning strike.

Nonetheless, using staggered observations we have made a statistical study between different stations to focus on the characteristics of VLF bursty-patches detected on the ground in Finland. Bursty-patches are emissions exceeding the local electron gyrofrequency that seem related to common VLF emissions (such as hiss or chorus) but have a different propagation mechanism that remains mostly unclear. Here we will discuss our findings and try to elucidate the exact propagation of VLF bursty-patches through simultaneous observations, polarization analysis, and estimation of ionospheric exit point. We will also investigate the potential effects of auroral precipitation and geomagnetic parameters on wave propagation through the ionosphere. Comparison with occurrence rates of usual VLF waves on the ground and in space might help us understand more about their relationship with bursty-patches.

## AS25-0510

# VLF bursty-patches observed at Angeli and Oulujarvi PWING VLF receivers located in Finland

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In recent years, the Japanese PWING project has allowed us to investigate the longitudinal characteristics of natural VLF emissions [1, 2]. Some interesting results from these previous studies have motivated us to focus on the latitudinal propagation and possible ionospheric propagation of certain types of VLF waves, particularly unusual high-frequency VLF bursty-patches [3, 4].

We will show the first results from the newest PWING VLF receiver installed on 21 August 2024 at Angeli (ANG, MLAT 66.3° N, L~6.2). Some comparison will be made with another PWING VLF receiver at Oulujärvi (OUJ, MLAT 61.7° N, L~4.5) and SGO's own VLF receiver at Kannuslehto (KAN, MLAT 65.0° N, L~5.6), although KAN receiver stopped in May 2024 due to a lightning hit an antenna pole and destroyed all the electronics. However, brief statistics are presented.

A few examples of filtered ANG and OUJ data will also be shown.

[1] Shiokawa, Kazuo, et al. "Dynamics of Plasma and Electromagnetic Waves at Subauroral Latitudes: Summary From the 7-year PWING Project." AGU23 (2023).
[2] Martinez-Calderon, C., Oonishi, T., Shiokawa, K. et al. (2023). Characteristics and longitudinal extent of VLF quasi-periodic emissions using multi-point ground-based observations. Earth Planets Space 75, 148.
[3] Manninen, J., N.G. Kleimenova, C. Martinez-Calderon, L.I. Gromova, and T. Turunen (2022). Unexpected VLF bursty-patches above 5 kHz: A review of long-duration VLF series observed at Kannuslehto, Northern Finland. Surveys in Geophysics, 44, 555-581.
[4] Martinez-Calderon, C., Manninen, J.K., Manninen, J.T. et al. (2021). A review of unusual VLF bursty-patches observed in Northern Finland for Earth, Planets and Space. Earth Planets Space 73, 191.

## AS25-0537

# The Exceptional Response of the Plasmasphere to the May 2024 Geomagnetic Storm

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According to the classical picture, the plasmasphere is considered a mere extension of the ionosphere into the magnetosphere. It is refilled from the underlying ionosphere during daytime and empties back into the ionosphere at nighttime via field-aligned plasma diffusion. During disturbed times, however, the plasmasphere can be severely eroded by the increased global convection electric field and other subauroral mesoscale electric field contributions.

In reality, the processes are even more complex, involving coupling and feedback mechanisms between the magnetosphere and the ionosphere. In investigating the May 2024 superstorm using plasmaspheric mass densities inferred from ground-based field line resonance observations along the EMMA array, we observed unique conditions.

Extremely high densities were observed within the severely contracted plasmasphere by the end of the storm's main phase. While a typical post-storm gradual refilling occurred outside the plasmapause during the early recovery phase on May 11, the extremely high plasmaspheric density decreased throughout the day. This behavior is typical at nighttime but exceptional during daytime. In the afternoon, a sudden density drop took place. The observations within the plasmapause cannot be explained solely by field-aligned plasma diffusion. Factors such as prompt penetration electric fields, disturbance dynamo electric fields, thermospheric winds, and mesoscale processes likely contributed to the observed plasmaspheric dynamics.

Another interesting aspect of this event was the unusually low resonance frequencies, which allowed several upper field line resonance harmonics to be observed at mid- and low latitudes. These harmonics can provide valuable information about the field-aligned density distribution during the evolution of the event.

## AS25-0594

# On the role of fine spectral features of high-amplitude waves in nonlinear scattering of radiation belt electrons

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Fast formation of high-energy electron populations in the Earth's outer radiation belt is primarily driven by resonant wave-particle interactions. These electrons pose a radiation hazard to spacecraft and can precipitate deep into the upper atmosphere, influencing its chemistry. Numerical models often treat these interactions as diffusive, following quasilinear theory, which assumes incoherent plasma waves with small amplitudes. However, intense and coherent electromagnetic waves can trap resonant particles and accelerate them to relativistic energies within seconds. Amplitude modulations or phase discontinuities reduce the efficiency of this nonlinear process, making the fine spectral structure of plasma waves crucial for assessing the validity of diffusive treatments. Here we focus on the electron interactions with whistler-mode chorus, examining three types of fine structure: (1) temporal overlap of neighboring spectral elements, (2) subpacket modulations along the propagation direction, and (3) amplitude modulation perpendicular to the local magnetic field line. We show that each of these features reduces the energy gain from nonlinear phase trapping. Subpacket modulations affect electrons across all energies and pitch angles, increasing the stochasticity of trajectories. The effect of wave packet overlap is most significant at high energies and pitch angles, where resonant islands interfere in velocity space. Perpendicular modulations impact only ultrarelativistic electrons with large gyroradii but suppress acceleration most effectively. In all cases, phase discontinuities play a critical role in the emergence of diffusive behavior. Our numerical results highlight the need for a deeper understanding of small-scale wave features to improve electron scattering models used in global radiation belt simulations.

## AS25-0659

# Role of adiabatic and non-adiabatic processes in the evolution of relativistic electrons in the radiation belt during geomagnetic storms

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The adiabatic and non-adiabatic behavior of relativistic electrons in the outer radiation belt during strong geomagnetic storms is investigated using simultaneous data from the Van Allen Probes and THEMIS satellites. Analysis of electron fluxes reveals an enhancement of relativistic electrons during the recovery phase, following a significant depletion during the storm's main phase. The peak electron flux occurs at an L-shell consistent with the Tverskaya relation. To determine the relevance of adiabatic mechanisms in explaining the behavior of relativistic electrons, we first analyzed the electron spectra and found that they are well-represented by a power-law function. At a fixed L-shell, the power-law index typically remains relatively constant during the pre-storm period, increases during the main phase, and decreases during the recovery phase. This prolonged conservation of the electron spectra slope suggests a dominant contribution from adiabatic processes, as it is challenging to attribute this effect solely to other processes like acceleration or losses of relativistic electrons. However, the substantial changes observed in the electron spectra slope during the storm phases may be related to alternative mechanisms that lead to electron loss or acceleration, such as interaction with ULF waves.

## AS25-0703

# Spatial distribution of Pc1/EMIC waves relative to the plasmapause footprint in the topside ionosphere

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Pc1 pulsations cover the 0.2–5 Hz frequency range with electromagnetic ion cyclotron (EMIC) waves of magnetospheric origin being generally accepted as their most important source. In the ionosphere, the initially transverse EMIC waves can couple to the compressional mode and propagate long distances in the ionospheric waveguide. By studying the Pc1 waves frequency range in the topside ionosphere, we can obtain information on the spatial distribution of both the transverse (incident EMIC) and the compressional waves. Recently, we have developed a new algorithm for automatic detection and characterization of Pc1/EMIC waves in the high-frequency magnetic measurements of the Swarm satellites. The resulting data product is now freely accessible to all users via ESA's dedicated web server [1]. In a recent study [2], we made use of this data product to explore the spatial distribution of Pc1/EMIC waves relative to the midlatitude ionospheric trough, which corresponds to the ionospheric footprint of the plasmapause (PP) at night. We showed that the occurrence peak of Pc1/EMIC waves is located equatorward of the PP footprint and that the spatial distribution of Pc1/EMIC waves closely follows changes in the PP location at all levels of geomagnetic activity. In the present contribution, in addition to discussing these results, we present our preliminary findings on the coherence of the Pc1/EMIC waves detected by the three Swarm satellites.

[1] https://earth.esa.int/eogateway/activities/swarm-ulf-ionosphere.

[2] Bozóki, T., and Heilig, B. (2025). Spatial Distribution of Pc1/EMIC Waves Relative to the Nightside Ionospheric Footprint of the Plasmapause. JGR: Space Phys., 130(2), e2024JA033385. https://doi.org/10.1029/2024JA033385.

## AS25-0783

# Investigating the statistical properties and underlying distributions of critical variables that govern whistler-mode chorus wave-particle interactions

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The behaviour of high-energy electrons in Earth's outer radiation belt is strongly influenced by wave-particle interactions, which are often modeled using diffusion coefficients derived from quasi-linear theory. Given the considerable variability in both wave and plasma properties within the outer belt, characterising these fluctuations in localised regions of the inner magnetosphere is essential.

Using observational data from Van Allen Probe A, we examine the statistical properties of several critical variables, including electron number density, magnetic field strength, and the ratio of electron plasma frequency to electron gyrofrequency. By exploring the co-variation between these plasma properties and evaluating the sensitivity of diffusion coefficients to changes in these variables, we aim to improve diffusion coefficient modeling.

Due to the substantial spatiotemporal variability in the diffusion coefficients, selecting an appropriate grid size for the variability analysis is crucial. An optimal grid size will help distinguish between temporal and spatial contributions in satellite observations, ensuring that the analysis captures both localised and broader-scale dynamics within the magnetosphere.

Furthermore, we investigate the underlying probability distribution functions of electron number density and the $\omega_{pe}/\omega_{ce}$ ratio by fitting suitable distributions to these variables to determine their fitting parameters. We will also explore the temporal variability scales of each parameter. This approach will support improved modeling efforts and enhance the reliability of conclusions drawn from these analyses.

## AS25-0805

# Drift phase structures: signatures of impulse or ULF resonance?

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This presentation will deal with transient features present in radiation belt spectrograms called drift phase structures. Their observations have multiplied over the last decade, thanks to the use of instruments with high-energy resolution, so much so that they are now viewed as a ubiquitous – and universal – radiation belt attribute. Yet, what exactly generates drift phase structures remains unclear. While well accepted as a mark of radial transport, drift phase structures are sometimes interpreted as drift echoes resulting from impulsive electric field perturbations and sometimes viewed as evidence of drift resonance with ultra-low-frequency waves. However, we still do not know the relative importance and efficiency of these processes.

This presentation will focus on a remarkable case in which drift phase structures were present over a broad energy range (from 50 to 600 keV) during an entire orbit of the Van Allen Probes mission. We will show how field and particle measurements can be leveraged to get experimental information on the possible generation mechanisms of drift phase structures. This approach represents a necessary step towards a comprehensive understanding of radiation belt dynamics.

## AS25-0848

# Specification of the in-situ natural wave environment from ground based VLF data

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Energetic electrons in the outer radiation belt can undergo gyroresonant interaction with various magnetospheric wave modes including whistler-mode VLF chorus outside the plasmasphere and whistler-mode hiss inside the plasmasphere. Theresult of this process can be the energization and precipitation of the energetic electrons by pitch angle or energy scattering. The calculation of diffusion coefficients requires the wave power of these waves at the wave-particle interaction region. This is available only for certain locations and times from in-situ measurements of recent science missions (Van Allen Probes, Arase missions) and not in real-time. Whistler mode waves below the half of the equatorial gyrofrequency can propagate in ducted/field aligned mode along the magnetic field line to the ground, The wave power measured on the ground by Automatic Whistler Detector and Analyzer Network (AWDANet, Lichtenberger et al., 2008, JGR) is used to estimate the in-situ wave power combining propagation models, such as ducted propagation model in the magnetosphere and the Stanford Full Wave Model ( FWM, Lehtinen and Inan , 2009, GRL) for trans- and subionospheric propagation. The models were calibrated and validated by chorus, hiss and VLF transmitter data measured by EMFISIS instrument on Van Allen Probes. The estimated wave power is used in Forecast of Actionable Radiation Belt Scenarios (FARBES, https://farbes.eu) HE project in Salammbo Radiation Belt model upgraded to use ground-based drivers.

## AS25-0922

# Kappa distributions and wave-particle interaction in the radiation belts and ring current

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Kappa distributions which typically possess an enhanced high-energy tail are ubiquitous in space plasmas, including the Earth's radiation belts, ring current and plasma sheet. We introduce a new kappa distribution which incorporates as special cases the familiar bi-kappa, kappa loss-cone, bi-Maxwellian,and Dory-Guest-Harris distributions. The new kappa distribution provides two sources of free plasma energy,namely the thermal anisotropy and the loss-cone property. We use the new distribution to analyze kinetic instabilities in the inner magnetosphere involving for instance ELF, VLF,and EMIC waves. We investigate the following wave phenomena: (a) linear growth of whistler mode waves generated by an injection of hot electrons into a cold plasma, (b) dispersion of R-mode and L-mode electromagnetic waves in a hot plasma, and (c) transition from linear to nonlinear growth of electromagnetic waves as determined by a critical boundary in the input-parameter space. In general we find that the influence of kappa distributions on kinetic instabilities is complex, not least because the instabilities depend on several system parameters as well as kappa.

## AS25-0924

# Contribution of poloidal Pc4 waves to the acceleration of electrons of the outer radiation belt to MeV energies

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Most researchers associate the acceleration of electrons at the outer radiation belt to relativistic energies (~1 MeV) either with their interaction with ULF waves (toroidal Pc5 pulsations) or with VLF chorus emissions. However, the growth of Pc5 and VLF activity in the magnetosphere ends, as a rule, before the start of the growth of relativistic electrons, and their flux reaches a maximum already after a magnetic storm. Therefore, the question arises as to what mechanisms are responsible for the relativistic electron fluxes continuing to increase after the decline in Pc5 and VLF activity.

In our opinion, poloidal Pc4 pulsations can be a quite likely candidate for the role of an electron accelerator up to MeV energies. These waves are observed only under calm geomagnetic conditions; they can last for several days. The report presents cases where Pc4 pulsations were recorded by the GOES satellites during a period of increasing relativistic electron fluxes. Observations show that the rise and fall of MeV electron fluxes in geostationary orbit occurs almost simultaneously with the rise and fall of energetic proton fluxes (95 keV). Thus, Pc4 pulsations turn out to be an agent that transfers energy from energetic protons to electrons of MeV energies. The mechanism of excitation of Pc4 waves and subsequent acceleration of electrons is associated with the resonant drift-bounce interaction of waves and particles.

The study was supported by the Russian Science Foundation grant № 25-17-20038.

## AS25-1026

# Two stage wave-particle-wave interaction recorded by the DEMETER satellite during magnetic superstorms

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It is generally accepted that the ionosphere is an excellent plasma laboratory. DEMETER with its extensive instrumentation can be traead as a tool for the study of non-linear processes generated by strong disturbances in the Earth's environment. Data recorded by energetic electron spectrometers, thermal electron density and temperature detectors and wave analysers in the ULF/ELF, VLF and HF frequency ranges have been used to analyse the processes shown in this presentation.

The French microsatellite DEMETER, operating from July 2004 to December 2010 in a circular orbit with an inclination of about 80° at an altitude of 660 km, recorded more than 30 storms with Dst below -100 nT and 3 superstorms, which we analysed in detail. The non-linear process shown here consists of two stages—first acceleration of electrons by ULF/ELF and second energetic electron generation waves in VLF and HF waves. This process affects the surrounding ionospheric plasma, causing strong variations in electron temperature and density. Thanks to DEMETER's orbit, these processes can be observed in different regions of the ionosphere.

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## AS25-1128

# Computer vision guided analysis of plasma waves in the inner magnetosphere

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Plasma waves like chorus, hiss, and lightning-generated whistlers (LGWs) drive radiation belt dynamics by accelerating and scattering electrons. Chorus waves energize seed electrons to relativistic levels, while all wave types contribute to electron loss via pitch-angle scattering. Missions such as the Van Allen Probes, Arase, DSX, and DEMETER have measured these waves using VLF receivers, offering insights into their effects.

A key challenge in studying plasma waves is distinguishing wave types. Manual classification, based on spectrogram analysis, is tedious and assumes prior knowledge of wave distributions. Fixed filter automatic identification can significantly reduce these burdens, but remains difficult to implement due to the overlapping frequency ranges of hiss, chorus, and LGWs, and susceptibility to spacecraft noise.

Therefore, our study develops a database of LGWs, chorus, and hiss using a computer vision model. Spectrograms are generated from Van Allen Probes B-field burst data, and a YOLO v8 machine learning model is trained to classify wave structures, localize them within the image, and generate an annotated dataset. This automated approach has been applied to seven years of data and presents early analysis of these plasma wave distributions. Future work aims to extend this method to DSX, Arase, and DEMETER data. The resulting database will support other studies of VLF wave distributions across L-shell, MLT, longitude, and geomagnetic conditions (Dst, Kp).

## AS25-1152

# Analyzing the relativistic electron response to varying geomagnetic storm conditions

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The relativistic electron response to geomagnetic storms in the radiation belt is significantly variable, but dependent on known upstream solar wind conditions and various measures of geomagnetic activity. Despite many decades of research, it is still unclear precisely the makeup of radiation belt drivers which result in observed activity. In this study, we utilize the uniquely large data set of the Proton Electron Telescope (PET) instrument, aboard the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) spacecraft, to statistically analyze this electron response to varying geomagnetic conditions. Furthermore, we investigate the change in flux in two temporal intervals of a geomagnetic storm, finding that solar wind speed was the strongest driver of electron flux recovery at higher L-shells. Other geomagnetic parameters varied in their influence on the electron population, while others show no correlation. Lastly, it is widely known that coronal mass ejection (CME) and corotating interaction region (CIR) driven storms share similar and contrasting effects on the radiation belts. To investigate this, we categorized storms from the SAMPEX era to be CME or CIR driven storms and reanalyze the correlation of the response of electrons to geomagnetic storm conditions. This study provides a new insight into the specific contributors to radiation belt storm-time dynamics.

## AS25-1182

# Investigating chorus wave peak amplitudes on short timescales during the Van Allen Probes era

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Earth's radiation belts can be described by two zones containing energetic charged particles; a more stable inner belt, and a highly dynamic outer belt. Wave-particle interactions have been identified as one of several processes responsible for the dynamics of electron populations within the outer region. The most common method used by the international community for reproducing radiation belt dynamics involves Fokker-Planck diffusion models. Whilst, in many cases, these models effectively describe the global changes and interactions within the region, the Fokker-Planck approach depends upon a quasilinear theory. This assumes "small" wave amplitudes; however, recent observations have shown that this assumption may not always hold, with chorus waves being one of the most notable cases of high-amplitude waves.

Within two datasets of differing resolutions, the Van Allen Probe satellites provide multiple years' worth of information on the various waves and background fields inside the radiation belts. In this work, we present results of investigations comparing the lower resolution 'survey mode' data, with the high-resolution 'burst mode' data, captured during the mission. In particular, the work focusses on identifying chorus wave events in both datasets and assessing how the underlying variability may alter our interpretations of the wave properties. Utilizing the higher resolution data in conjunction with the survey data allows closer inspection of the larger amplitude waves, and their potential implications for energetic electron dynamics in radiation belt modelling.

## AS25-1263

# Bridging the Data Gap: Deriving Complete Electron Boundary Conditions from Incomplete Satellite Observations for Radiation Belt Modelling

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The state-of-the-art BAS Radiation Belt Model (BAS-RBM) is a global model of Earth's radiation belts. Through integration with data from flagship satellite missions such as RBSP and Arase, the model enables investigations into wave-particle interactions, long-term radiation belt behaviour, and forecasting of radiation belt fluxes up to 24 hours in advance.

The BAS-RBM is driven by diffusion coefficients and boundary conditions, derived from real-world observations. To drive this model, we require the complete electron flux pitch angle distribution across various energies and L-shells throughout the simulation period. As we will show, however, even with advanced satellite data, inherent gaps make it impossible to rely solely on observations. Therefore, modelling, interpolation, or other techniques are crucial for filling these data gaps. This presentation will focus on the process of deriving the electron boundary conditions required by BAS-RBM, explaining new approaches we have developed to connect satellite observations with our model input requirements. Finally, we evaluating the success of our approach through comparisons with real events.

## AS25-1311

# New Chorus Diffusion Coefficients at Geosynchronous Orbit and Beyond

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Whistler-mode chorus waves are electromagnetic emissions in the Earths' magnetosphere that play a crucial role in the dynamics of the outer radiation belt, contributing to both acceleration and loss of relativistic electrons. Traditionally, the diffusion rates caused by these waves are calculated with the use of global models of wave spectra and independent models of the ratio of the electron plasma frequency to the electron gyrofrequency ($f_{pe}/f_{ce}$). However, more recent studies have demonstrated the importance of using co-located observations of the wave spectra and $f_{pe}/f_{ce}$. In this study the distribution of chorus waves, parameterised by $f_{pe}/f_{ce}$, as observed by three THEMIS spacecraft (THEMIS -A, -D, and -E), is investigated in relation to various solar wind parameters and geomagnetic indices. These co-located measurements of the wave spectra and plasma properties observations are used to compute bounce and drift averaged chorus diffusion coefficients. We present our latest results that demonstrate the role of equatorial chorus has on both acceleration and loss from the plasmapause to high L* (L* ~ 10). The derived diffusion rates are compared in overlapping regions with existing diffusion coefficients derived from Van Allen Probe measurements of the coupled wave spectra and plasma properties, which are more limited in spatial range and do not extend beyond geosynchronous orbit.

## AS25-1337

# The influence of cold plasma density on radiation belt enhancements

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The background plasma density in the magnetosphere determines the behavior of wave growth and wave-particle interactions that shape the warm and hot plasma including the ring current and radiation belts. Specifically, the ratio between the cyclotron frequency and the plasma frequency is a critical number that controls these interactions. To assess the potential role of cold plasma density in the formation of radiation belt enhancements and dropouts, we analyze this ratio over the entirety of the seven-year Van Allen Probes mission to look for statistical patterns in cold plasma density values, particularly where the ratio dips to very low values which implies stronger scattering interactions with higher energy electrons. We also conduct diffusion simulations to examine how low densities in particular areas of the inner magnetosphere might affect wave-particle scattering of radiation belt energy particles, particularly the timescales over which that scattering occurs. Additionally, we examine case studies using in situ particle and wave data to understand the system-level effects of very low cold plasma densities. Overall, we find that anomalously low background densities can increase the pitch angle scattering rate by orders of magnitude for relativistic electrons in the inner magnetosphere. This study brings new insight into how cold plasma is integral in wave-particle dynamics.

## AS25-1473

# Numerical Modeling of Multidimensional Diffusion: Staying Positive

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It is challenging to combine wave-particle interactions with radial transport in a single simulation. The quasilinear diffusion approach greatly relaxes the required time resolution (by averaging over gyro-, bounce-, and drift periods), but coupling between changes in energy and pitch angle, expressed as a "cross" diffusion coefficient, leads most grid-based numerical algorithms to struggle even to maintain positivity of solutions to the multi-dimensional diffusion equation. Several well-established algorithms and two new ones will be reviewed and assessed. The first set includes: a change of variables to diagonalize the diffusion matrix, straightforward fully implicit and semi-implicit schemes, the SDE (stochastic differential equation) method, and the "layer" method. The newly proposed techniques include a modified finite volume scheme, and a semi-implicit scheme applied to a (nonlinear) diffusion equation obtained for g = log(f).

An alternative modeling approach pushes test particles in the global fields of large-scale MHD simulations; wave-particle interactions can be included by supplementing the test particle motion with stochastic terms ("random walks") that reproduce the local diffusion processes.

All of these approaches require extensive calculations of diffusion coefficients, which have the form of sums of multiple integrals (whose integrands in turn require root-finding for the cyclotron and Landau resonances). It is further desirable to reevaluate them frequently as the underlying plasma and wave properties also evolve. An old and a new method to estimate them rapidly, based on the mean value theorem and on scaling of appropriate quantities, respectively, will also be discussed.

# A24 Magnetotail Processes and Their Coupling with the Solar Wind and Ionosphere

## AS25-0078

## Evidence of Electron Energization up to Relativistic Energies in the Near-Earth Magnetotail during HSS and HILDCAA Events

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The high-intensity long-duration continuous auroral electrojet (AE) activity (HILDCAA) events are associated with enhanced alfvenic fluctuations during high speed solar wind streams (HSS). Relativistic electron flux in the inner magnetosphere strongly intensify during HILDCAAs. Physical mechanisms of this intensification are not well established yet. We study observations by Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft in the near earth plasma sheet at radial distances of 10 Earth radii, during a HILDCAA event. The observations revealed recurrent dipolarizations accompanied by plasma flow vortices, impulsive electric field enhancements, and increases in electron fluxes at energies of 100\,keV up to ~1\,MeV. Electron pitch angle (PA) distributions at THEMIS showed field-aligned flux enhancements at energies of 100\,keV, which indicates Fermi-type energization. Hypothetically, electrons gain energy up to ~MeV via repetitive bouncing through the acceleration region. Energization of ions was insignificant which led to Ti/Te~1. The increased Te^{1/2}/ne ratio might locally increase the Hall conductivity in the conjugate ionosphere, leading to ionospheric current intensification and strong $dB/dt$ observed on the ground.

## AS25-0082

# Storm-Time Plasma Sheet Convection: Global Patterns and the Dynamics of Mesoscale Bursty Flows

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During geomagnetic storms, the nightside magnetosphere experiences significant disturbances as multiple phenomena interact across scales. Enhanced convection and particle injections influence ring current development, while mesoscale structures like bursty bulk flows (BBFs) and dipolarization fronts transport plasma and magnetic flux within the plasma sheet. However, their specific roles during storms remain unclear.

We quantify magnetic flux transport using Geotail and MMS data, analyzing plasma sheet convection across storm phases (main and recovery) and distances from Earth. Our results show an elevated convection electric field with a dawn-dusk asymmetry. Flux transport on the dawn side is linked to faster plasma flows, while on the dusk side, it is associated with more dipolar fields. This aligns with recent findings on magnetotail reconnection sites and the presence of a dawnside current wedge (DCW) during ring-current intensification.

Using Geotail observations, we assess the contribution of bursty mesoscale flows to magnetotail flux transport. A superposed epoch analysis reveals that while BBF properties remain similar across storm phases, their contribution to total flux transport increases during the storm main phase mainly due to globally elevated convection.

Finally, we identify dawn-dusk asymmetries in BBF properties and occurrence between quiet and storm times, highlighting the complex storm-time magnetotail dynamics.

## AS25-0095

# Magnetotail plasma eruptions driven by magnetic reconnection and kinetic instabilities

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Rapid plasma eruptions explosively release energy within Earth's magnetosphere, at the Sun and at other planets. At Earth, these eruptions, termed plasmoids, occur in the magnetospheric nightside and are associated with sudden brightening of the aurora. The chain of events leading to the plasmoid is one of the longest-standing unresolved questions in space physics. Two competing paradigms have been proposed to explain the course of events. The first asserts that magnetic reconnection changes the magnetic topology in the tail, severing a part of the magnetosphere as plasmoid. The second employs kinetic instabilities that first disrupt the current sheet supporting the magnetotail and launch waves that trigger the topological change to eject the plasmoid. Here we numerically simulate Earth's magnetosphere at realistic scales using a model that captures the physics underlying both paradigms. We show that both magnetic reconnection and kinetic instabilities are required to induce a global topological reconfiguration of the magnetotail, thereby combining the seemingly contradictory paradigms. Our results help to understand how plasma eruptions may take place, guide spacecraft constellation mission design to capture these ejections in observations and lead to improved understanding of space weather by improving the predictability of the plasmoids.

## AS25-0101

# Dynamics of the Earth's magnetotail: equatorial and low-altitude observations

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Earth's magnetotail is the primary region of energetic electron and ion acceleration and further injection into the inner magnetosphere. Structure and dynamics of the Earth's magnetotail are essentially coupled with the ionosphere through field aligned currents and energetic particle precipitations. This presentation reviews the contribution of low-altitude ELFIN measurements to our understanding of meso-scale and small-scale elements of such coupling. ELFIN detectors collect energetic electron and ion (>50 keV) fluxes that can be used for remote sensing of magnetotail and for determination of impact on ionosphere provided by precipitations from the magnetotail. We show examples of ELFIN conjugated measurements with near-equatorial THEMIS and MMS missions, ground-based all-sky-imagers, and low altitude DMSP and POES satellites. These measurements are discussed in context of importance of low-altitude energetic particle dataset for investigation of self-consistent magnetotail coupling with the ionosphere.

## AS25-0102

# 3D Kinetic Insights into Magnetic Reconnection: X-Line Spreading, Dawn-Dusk Asymmetries, and Planetary Magnetotail Dynamics

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Three-dimensional kinetic simulations reveal the complex nature of magnetic reconnection under the Hall effect, governing X-line spreading and dawn-dusk asymmetries. Electrons transport the normal magnetic flux (Bz) dawnward at sub-ion kinetic scales, with the normal field suppressing reconnection onset while the reconnected Bz enhances it, leading to competing asymmetries that likely differ between Earth's and Mercury's magnetotails—insights relevant to the NASA MMS, MESSENGER, and ESA-JAXA BepiColombo missions. Particle-in-cell (PIC) simulations further show that X-line spreading is asymmetric, forming sharp cusp-like structures along the ion-drifting direction while the spread remains minimal along the electron-drifting direction. This preferential ion-drifting spread provides an additional explanation for the higher reconnection occurrence on Earth's dusk side. Simulations also suggest that turbulence from drift-kink instability suppresses X-line expansion rather than facilitates it. These findings underscore the need to move beyond 2D models to fully capture reconnection dynamics in planetary magnetotails.

## AS25-0105

# Observations of sustained relativistic electron fluxes in the storm-time lunar-distant magnetotail

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We report on prolonged enhancements of electron fluxes at energies up to 500 keV, observed by the lunar-orbiting Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) probes during their magnetotail traversal in the recovery phase of a magnetic storm. The minimum disturbance storm time index was Dst≈-200 nT. The energetic electron flux enhancements were associated with periodic auroral electrojet (AE) activations. The enhanced energetic electron fluxes were omnidirectional and observed near the magnetic equator. Although ARTEMIS detected earthward magnetic flux transport bursts with rates exceeding 2 mV/m, along with associated broadband electrostatic fluctuations, no direct correlations were found between these phenomena and the multi-100 keV electron flux enhancements. We discuss potential mechanisms responsible for the energetic electron flux enhancements in the mid-distant magnetotail.

## AS25-0108

# Effect of field line curvature scattering on precipitation and isotropy of energetic protons in the magnetosphere

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Although low-altitude observations of energetic particle fluxes have shown that isotropic precipitation results from field-line curvature scattering, it remains unclear whether this process leads to an isotropic distribution in the magnetosphere. In this study, we distinguished the low-latitude boundaries of the loss cone filling and the isotropic distribution of energetic protons in an energy range of 10–180 keV/q using middle-altitude (3–5 Re) off-equatorial observations made by the Arase satellite. The isotropic distribution boundary is defined by the ratio of proton fluxes at pitch angles of 0º–45º and 45º–90º for the northern hemisphere. The latitude of the isotropic distribution boundary exhibits energy dependence, such that higher energy protons remain isotropic at lower latitudes, implying isotropization of protons by magnetic field line curvature. Around the isotropic distribution boundary, the downward loss cone was filled, while the corresponding upward loss cone was empty due to atmospheric loss. The low-latitude boundary of the loss cone filling tended to be located at ~0.1º–0.5º lower latitude than the isotropic distribution boundary. A numerical model of field-line curvature scattering reproduced this latitude difference in the low-latitude boundaries of the loss cone filling and the isotropic distribution. These results suggest that effective pitch angle scattering occurs only near the loss cone on the field line with a larger equatorial curvature radius, resulting in loss cone filling, whereas it occurs over the entire pitch angle range on the field line with a smaller equatorial curvature radius, leading to the isotropic distribution.

## AS25-0194

# Interaction between the magnetic field topology and the plasma dynamics in the solar wind-magnetosphere system under the northward IMF condition

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We propose a new approach by treating the solar wind and the magnetosphere as an integrated single system, wherein the magnetopause is regarded as an internal structure. In this approach, we need to treat the physical processes as interactions between the magnetic field and plasmas. Then, the vacuum magnetic field which is a superposition of the Earth's main magnetic field and a uniform IMF can be regarded as the ground state of the solar wind-magnetosphere system because it does not have free energy. Therefore, the behavior of the solar wind-magnetosphere system is determined by the balance between the plasma force and the restoring force ("the mechanical principle"). Moreover, because the vacuum field has null points, this structure already includes the reconnection between the IMF and the magnetospheric magnetic field. Furthermore, the topology of the vacuum magnetic field is conserved even in the deformed structure under the northward IMF condition ("the topology conservation property"). We call this vacuum field the skeletal magnetic field. Therefore, our approach for the physical processes in the solar wind-magnetosphere system under the northward IMF condition is to manifest behaviors of the magnetic field and plasmas in terms of the mechanical principle under the constraints of the topology conservation property. Based on this approach, we can explain the magnetospheric magnetic field and plasma structure in a unified way. For example, the topology conservation property leads to the long extending closed field line region forming the plasma sheet in the magnetotail.

## AS25-0359

# Energetic Electron Dynamics During Substorms in the Magnetotail: Insights from ELFIN and CIRBE Observations

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Magnetospheric substorms are characterized by a prolonged growth phase involving current sheet thinning, followed by magnetic reconnection and charged particle acceleration during the expansion phase. In this presentation, we will provide a comprehensive view of the acceleration and formation of energetic electrons using low-altitude measurements from the ELFIN and CIRBE CubeSat missions. A key advantage of these measurements is their ability to capture the global magnetotail structure within minutes, offering a snapshot-like view of the radial distribution of energetic electron fluxes. We analyze the energy spectra of electrons accelerated during the expansion phase, the maximum energies attained, and the distinct spectral features observed in the magnetotail–radiation belt transition region. To validate our interpretation of low-altitude observations, we compare ELFIN and CIRBE datasets with results from RCM simulations and near-equatorial THEMIS measurements.

## AS25-0455

# On the Relationship between Energy Input to the Ionosphere and the Ion Outflow Flux under Different Solar Zenith Angles

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The ionosphere is an important source for magnetospheric plasma, particularly for heavy ions with low charge states. Quantifying outflowing ionospheric ions is one of the important subjects for magnetospheric studies, because outflowing ions populate the magnetosphere and thereby modulate its physical characteristics. To examine the possible effects of solar illumination, we investigated the dependence of outflowing ion number fluxes on solar zenith angle (SZA) by analyzing particle and field data obtained at 3000–4150 km altitude by the Fast Auroral SnapshoT (FAST) satellite from 7 January 1998 to 5 February 1999. The resultant SZA distribution of ion outflow events indicates that ion outflows with large fluxes ($>10^8$ cm$^2$/s) occur mostly under sunlit conditions (SZA < 90°). We derived empirical formulas between energy inputs (Poynting fluxes or electron precipitation) and outflowing ion number fluxes for various SZA ranges. The derived formulas show positive slopes, indicating that the outflow flux increases with increasing energy input. The outflowing ion number flux increases more steeply with increasing electron density in the loss cone or precipitating electron density (>50 eV) under sunlit conditions than that under dark conditions, while the slopes for the input Poynting fluxes show no clear dependence on SZA. Under dark ionospheric conditions, although weak electron precipitation can drive ion outflows with small fluxes ($\sim10^7$ cm$^2$/s), intense ion outflows ($>10^8$ cm$^2$/s) rarely occur probably owing to low ionospheric $O^+$ ion densities and/or a small scale height of $O^+$ ions.

## AS25-0593

# Magnetotail Processes and Ionospheric Dynamics: Unusual High-Latitude STEVE Event and Subauroral Flow Evolution

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High-latitude ionospheric electrodynamics and structures are significantly influenced by magnetotail dynamics and the interaction between the magnetosphere and the solar wind. Plasma sheet dynamics, in particular, play a critical role in the auroral oval and sub-auroral regions. Recent studies have highlighted the importance of mesoscale structures, such as auroral streamers—the ionospheric counterparts of bursty bulk flows—in the formation and evolution of fast subauroral flows. The discovery of extreme subauroral flows and a new optical phenomenon has further intensified interest in this region. While storms and substorms have traditionally been linked to the initiation of these fast flows and optical emissions, recent findings suggest that, in rare instances, quiet-time conditions can also trigger such events, underscoring the role of magnetospheric configurations in generating these ionospheric responses.

In this presentation, we discuss an unusual STEVE (Strong Thermal Emission Velocity Enhancement) event observed at high latitudes, approximately ten degrees poleward of previously documented occurrences. Satellite observations revealed extreme westward ion drift velocities typically observed in mid-latitude subauroral regions—rather than at high latitudes. This event occurred without a preceding substorm, deviating from the usual STEVE occurrence. High-latitude radars recorded rapid equatorward ionospheric flows, but GOES satellite data revealed no evidence of particle injections, suggesting a highly inflated inner magnetosphere. Additionally, observations indicate that these quiet magnetospheric conditions, along with low magnetotail temperatures, contribute to electron-dominant injections at geosynchronous orbit and the narrowing of the subauroral flow channel. These studies provide new insights into subauroral dynamics and raise key questions about how magnetospheric configurations influence ionospheric dynamics.

## AS25-0621

# Study of Time Variability of the Lunar Sodium Tail Brightness Using Ground-based All-Sky Images and Satellite data

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This work reports on the results of the lunar sodium tail brightness spanning 08 lunations between May 2013 and April 2014. An all-sky camera situated at low latitudes/tropical region obtained successfully imaging of this extend tail through a sodium filter at each lunation. During new Moon time, the geometry of the Earth, Moon and Sun is such that the anti-sunward sodium flux is perturbed by the terrestrial gravitational field, bending the trajectories of the Na atoms as they pass by the Earth, resulting in its focusing into a diffuse cloud into a higher density region of significantly increased column content, that extends beyond the Earth. Our results suggest that the sodium production from the lunar surface possibly increases by the solar wind particles impact, that consequently, modulates the lunar sodium spot brightness observed in the all-sky images. Although we believe in the existence of multiple mechanisms for explaining the lunar Na exosphere, our results suggest that the extend lunar sodium tail detected by all-sky images, like in this present paper, has a close relationship with Coronal Mass Ejections (CME). In this study, important features from these observations are presented and discussed.

## AS25-0633

# Jupiter's dynamic auroral polar regions and their connection to the magnetotail

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Jupiter's magnetosphere is internally driven by its strong, rapidly rotating magnetic field and Io's significant heavy ion plasma source. These drivers lead to dynamic auroral current systems and an extended magnetotail connected to Jupiter's polar regions. Until very recently, the nature of Jupiter's connection to the solar wind, or lack-thereof, has been a mystery. Since 2016, NASA's Juno spacecraft has been in an eccentric, polar orbit about Jupiter. Measurements of Jupiter's plasma characteristics and composition show its polar-most field lines can be topologically closed, with conjugate magnetic footpoints connected to both hemispheres. Additionally, these measurements provide evidence that certain mid-latitude regions are intermittently open to the solar wind. Furthermore, Juno observations have identified persistent ionospheric outflow and demonstrated ions can be accelerated into Jupiter's magnetotail via wave-particle coupling. This presentation will discuss the new insight Juno has provided into the relationship between Jupiter's polar regions, its magnetotail, and solar wind.

## AS25-0647

# Drivers of Composition Changes in the Plasma Sheet

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How the plasma sheet forms is a fundamental question in magnetospheric physics. The plasma sheet population has contributions from both the ionosphere and the solar wind, but how the relative contributions from the two sources depend on driving conditions, and what transport paths the ions take to reach the plasma sheet are not fully known. Composition can be used to track the source, using O+ as a tracer for the ionospheric source, and the He++/H+ ratio compared to that in the solar wind to track the solar wind source. It is well known that O+ in the plasma sheet increases during active times. While solar wind ions are expected to enter the magnetosphere through reconnection, there are indications that the highest contribution of solar wind plasma to the plasma sheet occurs during northward IMF. The entry during northward IMF may come either from double-lobe reconnection or from entry through the flanks in processes associated with Kelvin-Helmholz vortices or Kinetic Alfven waves. Using plasma sheet data from MMS, we explore the response of the plasma sheet density, temperature and composition to sharp changes in the solar wind and IMF. Types of changes examined include changes in the IMF, changes in the He++/H+ ratio in the solar wind, and changes in the solar wind density. Examining the timing and location of plasma sheet changes after a sharp transition will help clarify the transport pathways of both sources to the magnetotail.

## AS25-0743

# Remote-Sensing Magnetotail Dynamics from Low Earth Orbit with CINEMA

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CINEMA (Cross-scale INvestigation of Earth's Magnetotail and Aurora) is a NASA Small Explorer mission concept to investigate the role of plasma sheet structure and evolution in Earth's multiscale magnetospheric convection cycle. How the plasma sheet maintains steady convection and what determines when and how the magnetotail transitions to explosive convection remains a mystery. Revealing the aspects of plasma sheet structure that regulate convection has posed a formidable observational challenge, because it requires reconstructing plasma sheet evolution and its connection to dynamics across disparate scales—from global to mesoscale to kinetic. CINEMA provides the first system-level, cross-scale view of the magnetotail to overcome this challenge and answer this longstanding question.

CINEMA's nine satellites in polar low-Earth orbits quickly traverse the low-altitude footprint of the magnetotail, obtaining a snapshot of its radial profile in minutes. Each spacecraft carries an on-board auroral imager, particle sensors, and magnetometers. CINEMA obtains information about the structure of the magnetotail remotely through its imprint on particle pitch-angle distributions, providing an unprecedented view of particle isotropy boundaries over a wide range of energies. Mesoscale aurora and bursty energetic particle precipitation serve as tracers of specific mesoscale and kinetic-scale dynamics. Field-aligned currents (FACs) that connect the magnetotail to the ionosphere are sensed by measuring magnetic field variations at each satellite. Together, these observations reveal the physics underlying multiscale magnetotail convection.

## AS25-0800

# Jupiter's Alfvén surface and implications for magnetotail behaviour

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Jovian magnetospheric plasma is coupled to the ionosphere through Alfvén waves. Alfvén waves enable the transport of angular momentum and energy between the planet and magnetospheric plasma, a process that ultimately generates Jupiter's bright auroral emissions. However, past the Alfvén radius, the location where the radial velocity is greater than the Alfvén velocity, magnetospheric plasma is effectively decoupled from the planet, with fluctuations in the local magnetosphere no longer communicated back to the planet. Determining Jupiter's Alfvén surface is critical for interpreting drivers of auroral emissions, in situ data, and applications of numerical models. Previous studies that calculated the location of the Alfvén radius assumed an azimuthally symmetric magnetosphere and local-time independent magnetic field. Here, we employ a statistical description of the magnetic field that includes local time effects. We find a minimum Alfvén radius of 30 $R_J$ (Jupiter radii) at 6 LT, with plasma decoupled from the planet in the post-dusk through dawn sector. Furthermore, no Alfvén radius exists within 60 $R_J$ between 8 and 20 LT, implying that magnetosphere-ionosphere coupling occurs throughout this sector. Our results have implications of the interpretation of Jupiter's magnetotail behaviour and we suggest that it may behave similar to the heliospheric current sheet. Our results highlight the importance of local time considerations in MI coupling studies at Jupiter and offer new interpretations for local time dependent measurements and observations, such as the spatial distribution of reconnection events, outflow events with strong radial components, and the dark polar collar in the auroral region.

## AS25-0989

# Dynamic Evolution of Bursty Bulk Flows (BBFs) Revealed by Two-way Coupled MHD-AEPIC Model and Multi-instrument Observations

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The dynamics of Bursty Bulk Flows (BBFs) is an outstanding magnetosphere-ionosphere coupling problem associated with sudden magnetic field topology reconfiguration and explosive current formation, particle acceleration, and energy release in the magnetosphere, and is believed to be playing a central role in geomagnetic disturbances, such as substorms. Using a two-way coupled magnetohydrodynamics with embedded kinetic physics model, we perform an event simulation to study electron velocity distribution functions (VDFs) evolution associated with BBFs observed by Magnetospheric Multiscale (MMS) satellite on May 16, 2017. Multiple ground and space-based instruments, such as Poker Flat Incoherent Scatter Radar and magnetometers, are used to reveal the MIT coupling features associated with this BBF event. The simulated BBF macroscopic characteristics and electron VDFs agree well with observations. The VDFs from the BBF tail to its dipolarization front (DF) during its earthward propagation are revealed and they show clear energization and heating. The electron pitch angle distributions (PADs) at the DF are also tracked, which show interesting energy dependent features. Lower energy electrons develop a “two-hump” PAD while the higher energy ones show persist “pancake” distribution. Our study reveals for the first time the evolution of electron VDFs as a BBF moves earthward using a two-way coupled global and kinetic model, and provides valuable contextual understanding for the interpretation of satellite observations. We also calculate the particle precipitation fluxes and field-aligned currents associated with the BBF and investigate the wedgelet formation.

## AS25-1012

# Stepwise development of the near-Earth magnetotail associated with substorm onsets

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Our previous studies showed that an auroral onset arc develops stepwise at the onset of a substorm: initial auroral brightening, enhancement of the onset arc, and poleward expansion. Corresponding to the auroral development, ground magnetic field perturbations and Pi2 and Pi1 pulsations at high and low latitudes also develops stepwise. To understand the substorm triggering mechanism, we study the connection of the stepwise auroral onset arc development with substorm-associated near-Earth magnetotail processes of magnetic reconnection, flow, wave, and dipolarization, using data from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) ground-based all-sky imagers and spacecraft. We show that near-Earth magnetic reconnection possibly occurs before initial brightening. At further enhancement of the onset arc, in the near-Earth region, the plasma and total pressures slightly increase, and low-frequency waves at ~1 min period amplifies, possibly due to arrival of the earthward flow generated by near-Earth reconnection. Near-Earth dipolarization may begin at this stage. Full-fledged dipolarization begins at poleward expansion. In addition, we show that ballooning instability in the near-Earth region grows more and more at each auroral step, including further enhancement of the auroral onset arc. Based on these observations, we discuss a possible scenario of near-Earth magnetotail development in the substorm onset phase.

## AS25-1061

# Dynamics of magnetotail thin current sheets during substorm growth phase diagnosed by low-altitude isotropy boundary observations

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Accurate mapping is important for studying of ionospheric signatures of processes at the magnetotail distances or interhemispheric conjugate signatures of the aurora. The substorm growth phase is characterized by the significant magnetic field line stretching and the formation of a thin current sheet in the equatorial magnetotail. Observations of ion and electron isotropy boundary (IB) at low altitude satellites, can probe, though indirectly, the dynamics of the inner edge of the magnetotail thin current sheet during substorms. We selected several substorm growth phases when IBs were clearly observed by the energetic particle detectors (EPDs) for ions and electrons onboard ELFIN CubeSats. ELFIN night-side observations were complemented with magnetic field measurements at THEMIS probes in the magnetotail. The obtained characteristics were utilized for constrain parameters of a new thin current sheet module, which was added into modified TS05 magnetospheric magnetic field model. For each observation of IB location (latitude and local time), by employing TS05 model, we traced the corresponding magnetic field line to its crossing in the magnetotail at Bmin point and computed the Rc/ρ-ratio for a specific particle energy there. The new thin current sheet module was incorporated into the TS05 model with varying its characteristics to fit the obtained Rc/ρ-ratios with the theoretically determined threshold (Rc/ρ=8) for strong pitch angle scattering. Magnetic field measurements from THEMIS probes were used to tune the Rc/ρ-ratios calculations. We present the results of our investigations of the dynamics of the thin current sheets during substorm growth phase diagnosed by low-altitude IB observations.

## AS25-1244

# Thin current sheet effects on substorm dynamics in the magnetotail

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Ion-scale thin current sheets (TCSs) are often observed in the magnetotail during the substorm growth phase. However, their structure and persistence in the growth phase, as well as their transformations in the expansion and recovery phases are not well understood. TCS are inherently a kinetic feature as their thickness is comparable to the ion gyroradius (or inertial length). Further, TCS are necessary to explain the observed current density as a function of distance along the tail. It is well known that isotropic force balance cannot explain current sheets that match observations, and instead are far too short. This leads to magnetic reconnection occurring too close to Earth (~10–12Re) whereas observations typically observe reconnection beyond ~20Re in the tail. It is necessary to understand TCSstructure and dynamics in order to incorporate their effects in global MHD simulations. We will present on simulations of driven magnetotail TCS and compare them to isotropic simulations.

## A25 Synthesis of Planetary Magnetosphere Models and Spacecraft Data

### AS25-0039

# Evolution of the flux tube instability parameters in plasma injections at Saturnian magnetosphere

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The evolution of the flux tube stability parameters in plasma injections at the Saturnian magnetosphere is presented. Plasma injections result from an imbalance in the centrifugal, total pressure gradient, and magnetic tension forces acting on plasma in the magnetosphere. Plasma originating from Enceladus tends to move outward due to centrifugal forces while reconnected flux tubes that are depleted of plasma collapse because of the magnetic tension leading to plasma injections. As the flux tube moves inward and contracts, the ambient density and pressure increase sufficiently to resist further collapse and the injected flux tube brakes. During this process the flux tube may also lose its integrity due to particle drifts, which allow exchange of plasma with adjacent flux tubes so as to bring the flux tube closer to equilibrium and stability so that it is indistinguishable from adjacent plasma. Stability parameters using this energy approach are defined and examined. The results show that the net forces push the plasma moves inward for L>11 and outward for L<8.5, while equilibrium is generally reached for 8.5< L< 11, where L is the equatorial magnetic field crossing measured in Saturnian radii. The evolution of the stability parameters can also apply to Jovian and other fast rotating planetary magnetospheres.

## AS25-0268

# Quasi-periodicities in the giant planet magnetospheres: Elucidating mass and magnetic-flux transport

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The giant planet magnetospheres exhibit periodicities ranging from the order of one hour to greater than the planet's rotation rate (i.e., > 10 hours and up to a few days). Global reconfigurations are expected to occur as part of the Vasyliunas cycle of reconnection with flux tubes on the night side stretching in the dusk region and eventually reconnecting toward the dawn region. At Saturn, observational evidence of tail reconnection indicates a recurrence rate of one plasmoid every ~2.4 days. However, it has been noted that small-scale reconnection occurs in the noon and dusk sectors, or "drizzle" reconnection. Additionally, the noon and dusk sectors exhibit a preponderance of quasi-period 60 minutes (QP-60). To date, little progress has been made on understanding the long-timescale periodicities of the magnetosphere and how dayside/dusk reconnection is intertwined with tail reconnection to satisfy global magnetic flux conservation. Understanding these periodic behaviors is critical to understanding mass loss and magnetic flux circulation. We will present quasi-periodicities at both Jupiter and Saturn and compare with results from Grid Agnostic MHD for Extended Research Applications (GAMERA) simulations.

## AS25-0287

# Dawn—dusk asymmetries in Jupiter's magnetosphere: model—data comparisons

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Jupiter's rapidly rotating magnetosphere, with internal plasma sources such as the volcanic moon Io, provides a unique natural laboratory for studying internally driven planetary magnetospheres. Using the Grid Agnostic Magnetohydrodynamics for Extended Research Applications (GAMERA) model, we simulated Jupiter's magnetosphere with ionospheric Pedersen conductances ranging from 0.5 mho to a million mho to investigate its role in controlling mid-magnetosphere region's dynamics and the closing of magnetosphere-ionosphere currents. Simulated density, temperature, and radial and azimuthal flows in the equator are compared with observations from the Jovian Auroral Distributions Experiment (JADE) on the Juno spacecraft. All simulation cases exhibit dawn-dusk asymmetries, in both the ionosphere and magnetosphere. The 0.5 mho case showed the best agreement with JADE observations, while the 1 mho case exhibited a magnetic topology more consistent with the auroral observations from the Hubble Space Telescope and Juno. These results enhance our understanding of Jupiter's magnetosphere-ionosphere coupling, provide context for observations, and inform the parameters of future test particle simulations and data-model comparisons using the GAMERA model.

## AS25-0387

# Comparison of the polar regions of Earth and Jupiter

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Juno observations of Jupiter's polar cap indicate a region with very low plasma density together with the downward acceleration of heavy ions (oxygen and sulfur) to megavolt energies. Auroral "swirl" regions occupy this region, indicating particle precipitation. On the other hand, the Earth's polar cap is largely devoid of auroral emissions other than transient polar cap arcs. These observations suggest that large parts of Jupiter's polar cap is on field lines that map into the plasma sheet, while on Earth the polar cap appears to be largely open to the solar wind. While the density and temperature of the polar ionospheres seem to be similar at both planets, the composition is quite different, consisting mainly of oxygen ions and protons at Earth but mainly protons and $H_3^+$ molecules at Jupiter. This composition difference, together with the stronger gravitational field at Jupiter, may be significant in the different behavior of the two regions. The observations from Juno will be combined with fluid and kinetic modeling of these regions to help understand the differences.

## AS25-0388

# Statistical survey of magnetic flux integral quantities in Saturn's magnetosphere

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Magnetic flux integral quantities (e.g., flux tube entropy, flux tube content) are conserved quantities under the frozen-in assumption. The change of these quantities often indicates the violation of the frozen-in condition (e.g., interchange instability). In this study, we combine the Cassini CAPS and CHEMS Moments Data as well as a steady state magnetic field model (i.e., Caudal model) to estimate the flux tube content and flux tube entropy in Saturn's magnetosphere. Our statistical survey found the flux tube content rapidly decreases with the radial distance away from Saturn in the inner magnetosphere and roughly levels out in the middle magnetosphere, indicating the radial transport processes occurring in the inner magnetosphere and the middle magnetosphere could be fundamentally different. Notice, that Saturn's magnetosphere is stabilized by a radially increasing profile of flux tube entropy and destabilized by a radially decreasing profile of flux tube content. In this study, we also estimate the expected penetration location by using the flux tube interchange stability formalism developed by Southwood and Kivelson (1987). The results show that flux tube entropy can play a crucial role in braking the injections, while the flux tube content has a relatively smaller influence on the injected flux tube, being consistent with our previous case study by Wing (2022).

## AS25-0488

# Estimations of soft X-ray emission from Uranus's magnetosheath

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Within planetary magnetosheaths, charge exchange between highly charged solar wind ions (such as $O^{7+}$) and neutrals produces soft X-ray emission. This emission provides a global, dynamic view of the magnetosheath and allows exploration of the driving of the magnetosphere by the solar wind. Uranus, visited only by Voyager 2 in 1986, has a highly asymmetric magnetosphere where cusps can directly face the solar wind. Neutrals sputtered from the icy moons form tori that extend beyond the magnetosheath. We present the first model of soft X-ray emission from Uranus's magnetosheath considering equinox and solstice configurations as well as different solar wind conditions. Volumetric emission is on the order of $10^{-10}$ photon $cm^{-3}$ $s^{-1}$, with equinox emission rates being twice as high as solstice. Within ~250 $R_U$ during Uranus approach, a SMILE-like SXI would be able to image photons with integration times much less than a planetary rotation period. Under a point source approximation, imaging is feasible out to ~10 au, enabling over a year of observation before arrival. These results indicate that soft X-ray imaging is a potentially valuable tool for studying Uranus's magnetosphere and support further model development.

## AS25-0734

# Model-based interpretation of Rosetta plasma density observations from comet 67P

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The Rosetta spacecraft escorted comet 67P/Churyumov-Gerasimenko for two years, gathering a rich and variable dataset. Among the data from the Rosetta Plasma Consortium (RPC) suite of instruments are measurements of the total electron density from the Mutual Impedance Probe (MIP) and Langmuir Probe (LAP).

At low outgassing, the plasma density measurements can be explained by a simple balance between the ion production through photo- and electron-impact ionisation and loss through radial transport (Galand et al 2016, Heritier et al 2018). Ion motion is consistent with that of neutrals, that is, travelling radially at the same outflow speed. Near perihelion, the assumptions of this field-free chemistry-free model are no longer valid, and such an approach overestimates the plasma density. This can be explained by enhanced ion transport by an ambipolar electric field (Lewis et al 2024) inside the diamagnetic cavity, free of the interplanetary magnetic field.

We explore the transition between these two regimes, at intermediate outgassing, when the interaction between the cometary and solar wind plasmas influences the transport of the ions. We use a 3D collisional test-particle model, adapted from Stephenson et al (2022) to model the cometary ions with input electric and magnetic fields from a hybrid simulation for 2.5–3 AU. The total plasma density from this model is compared to data from MIP/LAP and to the field-free chemistry-free model. We highlight the limitations of the hybrid approach and demonstrate the importance of modelling collisional cooling of the electrons to understand the ion dynamics close to the nucleus.

## AS25-0829

# Investigating solar wind interactions at Jupiter's mid-latitude dusk magnetopause

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A large impact on our understanding of the dynamics near Jupiter's magnetopause can be made by analyzing the plasma and magnetic field properties in relation to solar wind interactions and plasma transport near Jupiter's duskside magnetopause. Juno has now made several magnetopause crossings at Jupiter's duskside magnetopause at mid-latitudes (-29.5° to -45°). We analyze magnetosheath, magnetosphere, and boundary layer plasma and magnetic field properties to identify magnetic reconnection, KHI, and boundary layer mixing. Utilizing analysis methods from the Juno prime mission (e.g., Swisdak relation, KHI condition, total solid angle approach, and ion composition analysis), we conduct comparative statistical studies and surveys between the equatorial region on the dawnside magnetopause and the mid-latitude region on the dusk side magnetopause. We may also be able to better constrain the three-dimensional shape of the magnetosphere and provide an update to current Jovian magnetosphere models because of these higher-latitude magnetopause crossings.

## AS25-0937

# Mercury magnetosphere modeling in relation to the BepiColombo mission

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Mercury, the innermost planet of our Solar System, is the only other telluric planet, besides Earth, that possesses a global intrinsic magnetic field. Because of its proximity to the Sun and its weak intrinsic magnetic field, which is less than 1% of Earth's, Mercury's magnetosphere is highly dynamic and highly responsive to the variations in the solar wind conditions. NASA's MESSENGER observations showed that the system can completely reconfigure itself on the order of minutes. BepiColombo, the joint mission between ESA and JAXA, is currently en-route to Mercury, carries a sophisticated suite of instruments that will provide new data with unprecedented spatial and temporal resolutions. After several years of its cruise phase, the six Mercury flybys have been conducted and the BepiColombo has brought us variable data. To correctly interpret and analyze these local measurements, however, a substantial complementary modelling effort is required to provide a global context. In particular, the small magnetosphere of Mercury has been known to operate at kinetic scale where the plasma kinetics are expected to play a significant role. Beyond the synergy between spacecraft observations and simulations, comparing different simulation models is crucial for advancing our understanding of Mercury's magnetosphere and, more broadly, of magnetospheric dynamics across the Solar System.

## AS25-1054

# Transition from a Dungey convection- to rotation-dominated magnetosphere

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The general applicability of the classic Dungey cycle to planetary magnetospheres is controversial when planetary rotation is faster than the Earth. We demonstrate first-order modifications to transit a Dungey convection-dominated magnetosphere to a rotation-dominated one, using the Earth's magnetosphere as a testbed. By increasing the influence of planetary spin over solar wind merging, we show that when the rotation potential of the polar magnetosphere becomes comparable to the merging potential of the solar wind, the Dungey cycle is modified effectively by azimuthal transport of magnetic flux, resulting in flux pile-up and a more closed polar magnetosphere with crescent-shaped open flux region in the ionosphere. This study provides a theoretical framework describing the fundamentals of magnetospheric physics, which is applicable to the Saturn, Jupiter and exo-planets systems.

## AS25-1071

# Hybrid simulation of quasi-neutral plasma in gas giant magnetospheres

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Modelling of the plasma environment in fast-rotating gas giant magnetospheres is imperative to understand the mechanics of plasma transport through the system. Spacecraft observations are limited in coverage and detail even for our local exemplars, and acquiring more is time-consuming and expensive. JERICHO (Jovian magnEtospheRIC Ion kinetic fluid electron Hybrid plasma mOdel, [1]) contains functionality for modelling plasma behaviour at Jupiter or Saturn, with tools to simulate other planets if they meet certain criteria. The code can be run either in serial or in parallel using MPI, allowing a range of simulation complexities to be modelled efficiently.

Using estimated plasma injection rates from Io and average plasma parameters from JUNO/JADE as discussed in [2], JERICHO simulates bulk plasma transport and centrifugal interchange instabilities over a range of spatial scales. The simulated plasma is evolved in time for several hundred ion gyroperiods, which allows the model to settle from initialisation noise. This means that plasma features seen in the output data can be confidently assumed to be due to magnetospheric plasma physics.

The resulting plasma velocity, temperature, and density distributions are analysed post-processing and compared to spacecraft observations to understand the factors controlling radial plasma transport between in the Jovian magnetosphere.

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## AS25-1078

# A study of the Jovian current sheet in the Juno era, using a combined modelling approach

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We present a new study of Jupiter's magnetodisc that merges the UCL-AGA magnetodisc code with Khurana's generalized, hinged current sheet model (Khurana 1992). This combined approach enables us to capture both the large-scale morphology of the Jovian current sheet and the localized warping driven by the solar wind. Understanding these structures is also essential for interpreting the environment surrounding Jovian moons, such as Europa and Ganymede, where subsurface oceans are continually exposed to the periodic 'driving' field of the rotating, tilted current sheet.

Jupiter's magnetosphere is powered by a strong intrinsic field and the field of an extended current sheet, which can dominate at large radial distances (>~10 RJ). Solar wind pressure and flow direction impart additional hinging effects and further shape the global configuration. By analysing Juno magnetic field observations from several perijoves, we derive a revised set of current sheet parameters that characterize Jupiter's outer magnetosphere during the Juno era. Notably, our method includes isolating short-term epochs of stable magnetospheric conditions to distinguish longer-term variations in current sheet morphology from transient compression/expansion episodes. These transient events highlight the interaction between internal rotation-dominated processes and external drivers, revealing how solar wind dynamics modulate the global field configuration. Our results give insights into the system-scale balance of forces acting on the Jovian magnetosphere and highlight the importance of capturing both steady-state structure and short-lived perturbations. This added context may also assist future mission planning and data interpretation—particularly for isolating the magnetic signatures of subsurface ocean layers in Jupiter's moons.

## AS25-1407

# The Earth's magnetopause: a comparison between models (global MHD numerical simulations; one-dimensional Vlasov equilibria) and in-situ data (MMS2)

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In this study we compare the position and spatial profile (plasma density, bulk velocity, magnetic field, etc.) of the magnetopause (MP) as measured in-situ by MMS2 spacecraft with results from global MHD numerical simulations of the Earth's magnetosphere performed at National Aeronautics and Space Administration–Community Coordinated Modeling Center (NASA-CCMC), as well as with a Vlasov equilibrium modelling of the magnetopause. The global MHD simulations are initialized with solar wind conditions extracted from the OMNI database at the time epoch (October 16, 2015) when the MMS2 observes the MP and provide a time-dependent 3D picture of the MP. The kinetic steady-state Vlasov model uses asymptotic boundary conditions derived from in situ MMS2 measurements and provides a local, one-dimensional description. We found that the MP transition layer formed in global MHD simulations was generally localized closer to the Earth (roughly by one Earth radius) from the position of the real MP observed by MMS2. We also found that the global MHD simulations overestimated the thickness of the MP transition by one order of magnitude for three of the analyzed variables: magnetic field, density, and tangential speed. The MP thickness derived from the local Vlasov equilibrium fits better the observations. The overestimation of plasma density in the Vlasov equilibrium was reduced compared with the global MHD numerical simulations.

## A26 Auroral Dynamics

### AS25-0186

# On the orientation of nightside auroral arcs

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We present statistics and dependence on interplanetary conditions of the orientation of nightside auroral arcs in the equatorward part of the auroral oval. The dataset includes about 20,000 auroral arcs observed in Sodankyla (67.37° N, 26.63° E, Finland) during 2009–2021 or Abisko (68.36° N, 18.81° E, Sweden) during 2016–2021. The observations were made between 19 and 06 magnetic local time (MLT). On average, the orientation of the arcs, i.e., the angle between an arc and the geomagnetic West-East direction, linearly changes with MLT at the rate 2.2°/hour. In most cases the mean orientation of the auroral arcs gets parallel to the geomagnetic latitude at ΔT = 0.2–1.0 hours after the MLT midnight. The orientation of the arcs may be represented by a circle which center is shifted anti-sunward from geomagnetic pole by a distance D = 2.5–3.5° CGM latitude and rotated by the MLT angle corresponding to ΔT. The most prominent is a linear dependence of D on the solar wind pressure (Psw), such that it changes from 2.5° to 3.3° for the Psw increasing from 1 to 4 nPa, which is explained by increasing the Chapman–Ferraro currents at the magnetopause. There is also a less prominent and more complex dependence of ΔT on the solar wind speed and the interplanetary magnetic field, which indicates that ΔT is affected by the magnetospheric convection. One more factor affecting the orientation of arcs may be the neutral wind, which effect was indicated during spring transitions in the atmospheric circulations from winter- to summer-type.

## AS25-0233

# Characteristics of low-latitude auroras observed in Japan in 2023–2025 during the cycle 25 solar maximum

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The Solar-Terrestrial Environment Laboratory (STEL, 1990–2015) and the Institute for Space-Earth Environmental Research (ISEE, 2015-), both under the Nagoya University, Japan, have conducted routine measurements of low-latitude auroras in Japan using optical photometers and all-sky airglow/auroral cameras. We have observed 11 low-latitude red auroras in Japan during the solar cycle 25 in 2023–2025. This number is much larger than that in cycle 24 (only two) and is approaching to those in cycle 23 (18 events in 1999–2004). These observations were made at the Moshiri Observatory (44.37 N, 142.27 E, MLAT=35.6), Rikubetsu Observatory (43.46 N, 143.77 E, MLAT=34.7), in Hokkaido, and at the Shigaraki MU Observatory, Kyoto University (34.85 N, 136.11 E, MLAT=25.4), Japan. These low-latitude auroras were characterized by red emission at a wavelength of 630.0 nm. Some are also accompanied by green (557.7 nm) and faint blue (427.8 nm) emissions. Their appearance has long time scales of more than hours, while hourly-scale brightening and small-scale structures and their motion were also observed associated with the occurrence of magnetospheric substorm. In the presentation, we will summarize the characteristics of these low-latitude auroras observed in 2023–2025 during the cycle 25 solar maximum and discuss their possible generation mechanisms.

## AS25-0266

# Investigation on Properties of Field Aligned Electrons in Auroral Region

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Field Aligned Electrons (FAE) in polar space are significant to auroral process and take an important role to FAC and energy transfer. The Cluster data are used to study the features of the FAE over the polar regions. The FAE event is defined as electron parallel flux > $3\times10^8$ $(cm^2\cdot s)^{-1}$. The results show the longest duration of FAE event is 476 seconds. The FAEs are commonly distributed in the auroral oval and have two concentrations. The main concentration is around the cusp region and the other is in the evening section. The total number of FAE events around the two cusps is basically identical, but the downward FAE events prevail around the south cusp and the upward FAE prevail around the north. Around the southern cusp, the FAE flux peak is 1.3 $R_E$ higher at altitude and 4° lower at ILAT. Only the precipitation FAEs distribution in the southern cusp longitudes has a second ILAT peak which is 11° higher than the first peak. It indicates a north-south hemispheric asymmetry of the FAE distribution. The spectrum analyzing illustrates that the downward FAEs are of the precipitation electrons. Around the cusps the FAEs are mainly from solar wind, and in the nightside the FAEs are mainly from magnetotail. Several causes for the north-south asymmetry of the FAEs are discussed. The second ILAT peak of the precipitation FAEs around the south cusp longitudes corresponds to high solar wind speed, and may be associated with the NBZ FAC in the polar space.

## AS25-0596

# Inner magnetospheric and ionospheric responses to solar wind driving during omega band events

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Omega bands are a mesoscale auroral structure that appear as quasi-periodic eastward-drifting poleward protrusions in the closed field line region of the auroral oval. They are typically observed in the post-midnight sector during periods of geomagnetic activity. While the appearance of omega bands has previously been associated with solar wind driving similar to stream interaction regions, the magnetospheric and ionospheric response to this driving is not well understood.

We perform superposed epoch analyses of the solar wind, magnetospheric, and ionospheric parameters during 205 omega band events from 1997 to 2007. We find that omega bands are associated with either (a) enhancements in solar wind flow speed, or (b) enhancements in solar wind density that are coupled with an enhanced southward interplanetary magnetic field. In the ionosphere, omega bands are correlated with peaks in the intensity of the auroral electrojets. In the inner magnetosphere, the appearance of omega bands is associated with magnetic perturbations that are consistent with an activation of the partial ring current, which is supported by peaks in the local ring current indices. This analysis will contribute to identifying magnetospheric drivers of omega bands and the association between these drivers and compression regions in the solar wind, which will improve our understanding of magnetospheric and solar wind drivers of auroral dynamics.

## AS25-0602

# Associated dB/dt spikes with auroral signatures during lobes reconnection

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Strong solar eruptions lead to significant disturbances in the Earth's magnetosphere, measured as rapid changes in the magnetic field at the ground, known as large dB/dt and pose a space weather hazard to power grids and other infrastructure. As the interplanetary magnetic field or IMF changes its direction the dynamics of the magnetosphere are altered. Southward IMF Bz provokes low-latitude magnetopause reconnection, which can generate significant dB/dt spikes. Northward IMF Bz leads to high-latitude or lobe reconnection, which is thought to lead to relatively benign geomagnetic conditions. However, here we report that significant dB/dt spikes can also be produced by lobe reconnection.

Using data from the SuperMAG collaborative database and DMSP satellites, we investigated dB/dt spikes equal or greater than |300| nT/min and their associated auroral signatures for June 22–25, 2015 during the summer solstice geomagnetic storm. We found 13 DMSP conjunction passes geographically covering 54 dB/dt spikes. Out of these 13 passes, three conjunctions occurred between 12 and 18 MLT and are associated with single lobe reconnection. The dB/dt spikes are potentially associated with cusp spots and HiLDA signatures poleward of the auroral oval. These observations are very interesting while they occur in the middle of a geomagnetic storm main phase and not during quiet magnetospheric conditions as it could be expected. The study is one step forward and contributes to the global understanding of the lobe reconnection processus and its auroral signature.

## AS25-0628

# Optical observations and modelling to reconstruct precipitating particle fluxes and the ionosphere dynamics: new observations and uses of RGB images

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Optical observations of the aurora from space and from the ground give key information for auroral physics studies. They however often need to be coupled with simulations to give their quintessence. In our works, we use imagery, spectroscopy and polarimetry instruments to observe the auroras and combine these observations with a 1D kinetic code of the ionosphere thermosphere named Transsolo to get both the precipitation particles characteristics and the dynamics. Recent developments allow to get the full synthetic spectra of the aurora both in the FUV (120–200 nm) and in the visible (380–900 nm). By running the code at different locations on a grid it is then possible to map the precipitation using different parameters of the particle distributions, especially the total flux, the mean energy of the distribution(s) and their widths. By integrating over RGB filters bandpass, it is also possible to use RGB images to reconstruct these precipitating characteristics. Since this last activity is applicable to the amateur images, it is done in the frame of the ISSI ARCTICS group.

In this presentation, we will review these optical developments, the links with the simulations and their applications for auroral physics.

## AS25-0634

# Mean Energy Variability of Diffuse Aurora Observed with the ASIS Spectrograph

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Diffuse auroras are commonly observed during the recovery phase of auroral substorms, particularly in the morning sector. Among diffuse auroras, Pulsating Aurora (PsA) is the most common type, driven by the scattering of energetic magnetospheric electrons by chorus waves. Recent studies suggest that the energy of precipitating electrons in diffuse auroras increases throughout the night (Hosokawa & Ogawa, 2015), as chorus waves propagate toward higher latitudes in the magnetosphere, enabling more efficient scattering of higher-energy electrons (Ito et al., 2024). Since October 2023, the Auroral Spectrograph in Skibotn (ASIS) has been continuously monitoring auroral spectra in the visible range (405–687 nm) with a spectral resolution of 0.4 nm and a temporal resolution of 30 seconds. Using the auroral classification from Nanjo et al. (2022), we conducted a statistical study of over 20,000 spectra associated with diffuse auroras. Using the method of Adachi et al. (2017), we estimated the mean electron energy from the intensity ratio of the red (630 nm) and blue (427.8 nm) emission lines. Our results confirm that diffuse auroras predominantly occur in the morning sector, peaking around 3–4 MLT. Prior to 3 MLT, the mean precipitating electron energy is approximately 2 keV. However, after 4–5 MLT, electrons become more energetic, reaching a mean energy of ~4 keV. This trend supports the hypothesis that precipitating electrons harden as morning progresses, reinforcing the role of chorus waves in energizing magnetospheric electrons at later MLTs.

## AS25-0652

# Imaging energy transport and conversion above discrete aurorae

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Magnetically connected observations of particle distributions and luminosity from the Reimei spacecraft are used to examine energy transport and conversion occurring above a discrete auroral arc. By combining imaging and in-situ measurements it is shown how transverse electromagnetic and kinetic energy fluxes measured along the spacecraft trajectory converge across geomagnetic field-lines into the acceleration region. It is shown how cross-field energy transport is facilitated by the formation of vortices along the length of the arc. From an integration over the vertical extent of the acceleration region it is shown that the transverse and field-aligned flow of energy into the arc locally supports the dissipation needed to power the electron acceleration observed. Estimates of gradients in electromagnetic and kinetic energy flows show how field-aligned electron energization in the acceleration region is supported by the divergence of Poynting flux along and across the background magnetic field.

## AS25-0921

# The Auroral Vortex and Rolling Magnetic Carpet

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Vortices in any kind of medium are a strong indication of shears, and so are the auroral vortices. The uniqueness of auroral vortices is that the shear stress does not collocate with the illumination but in a remote region that can be thousands of kilometers or tens of earth radii away from the ionosphere. Shears provide free energy sources for the Kelvin-Helmholtz instabilities, leading to vortices in the plasma flow in the source region, which could be the remote driver of the auroral vortices. We report the events of the auroral vortex array recorded from Poker Flat during our 2023 winter campaign. Such arrays started from the beading of a pre-existing and stable east-west poleward arc just south of Poker Flat, then evolved to curls and spirals while extending eastward and northward, leading to a substorm expansion within only ~2 minutes. Based on multiple wavelength observations through the magnetic zenith, we found the average energy and energy flux were 6–7 keV and 30–40 mW/m^2 at the brightest vortex that has the dimensions of ~30x40 km. The auroral morphology strongly suggests electrons precipitated along a rolling magnetic flux analogy to the roll-up carpet that carries the upward FACs. A shear force in the remote source region may have rolled up the magnetic carpet via the Kelvin-Helmholtz instability and the resulting vortices. Instead of axial, the upward FACs warp with the rolling magnetic carpet embedded with microstructures or sublayers, which bridged the vortices in the ionosphere and the source region.

## AS25-0986

# Aurora Zoo: Statistical studies of fine scale auroral structure and dynamics through citizen science

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The aurora is rich in structure and dynamics on fine scales (< ~1 km). High cadence observation of structure on these scales provides a powerful route to understanding the physics of the acceleration mechanisms of the precipitating particles producing the aurora, as well as the nature of magnetosphere-ionosphere coupling and energy transfer into the neutral atmosphere. However, a significant challenge associated with these observations is that there is so much variability in the aurora, so categorising the structures and dynamics is not straight-forward and statistical studies are often difficult and time consuming, with the result that many studies in the literature consider only a small number of events. The Auroral Structure and Kinetics (ASK) multi-spectral imager has been observing fine-scale aurora in the high Arctic for almost 20 years (since December 2005), producing a substantial data set. To enable statistical studies of fine-scale aurora observed by ASK, we have developed a citizen science project called Aurora Zoo, through which members of the public classify short clips of ASK observations. Aurora Zoo also provides a means of identifying unusual events and types of aurora. Some results of studies utilising the classifications made in Aurora Zoo will be presented.

## AS25-1059

# Investigating the magnetosphere-ionosphere coupling currents driving auroral emission in Saturn's southern hemisphere

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In 2017, the final orbits of the Cassini-Huygens mission provided 22 low-altitude passes through Saturn's auroral region. Notably, magnetometer (MAG) data revealed asymmetric signatures between inbound and outbound passes in the dawn and dusk sectors respectively. Similar asymmetries have been observed in ultraviolet imaging. Given that Saturn's magnetic field is highly symmetric, with a FAC structure largely driven by plasma subcorotation that is also symmetric within the inner regions of the magnetosphere, these asymmetries suggest some additional processes are driving these variable features at broadly fixed local times.

Using data from Cassini MAG, we first process MAG data to determine ionospheric currents, whose gradient indicates FAC structure directed radially upward or downward. Orbits are categorized based on general FAC behaviour with colatitude, and each pass is individually analysed to assess its consistency within its group, variations across local times, and any correlation between FACs and auroral enhancements observed using Cassini UVIS, and/or Hubble Space Telescope STIS datasets, where images exist.

By comparing these groups generally, we investigate whether auroral enhancements and local time differences, or similarities, correlate with specific repeated FAC behaviour. Additionally, we examine the dependence of each group on Saturn's planetary period oscillation (PPO) FAC. Finally, our results are compared with previous studies to identify potential variations over longer timescales, and inter-hemispheric differences.

This work outlines the lack of axial symmetry in Saturn's FAC system and highlights the complexity of duskside auroral dynamics.

## AS25-1110

# Observing auroral dynamics: under, over and through

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We present findings on auroral events with key features that are used to illuminate their physical origins and drivers. We see significant correlation between optical characteristics and particle energies and fluxes which allow us to deduce processes in Earth's ionosphere and its critical connections to energy input from the magnetosphere. The ionosphere in particular is an important component of global magnetospheric models and common volume observations during auroral events offer a comprehensive technique for improving our understanding and hence our predictions of space weather. Many sounding rocket missions have targeted such events, focusing on time varying auroral structures including pulsating aurora. We combine multi-spectral all-sky and narrow field-of-view imaging of the aurora from the ground with in-situ high spatial and temporal resolution particle measurements in the range of hundreds of eV to tens of keV from sounding rocket payloads.

## AS25-1155

# ROKITS: a space-born imager for aurora and airglow

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The Republic of Korea Imaging Test System (ROKITS), a wide-field aurora and airglow imager aboard the CAS500-3 satellite, is set to launch in November 2025. Operating from a sun-synchronous orbit at an altitude of 600 km with a 90° field of view, ROKITS captures images approximately 700 km wide. It comprises three lens assemblies and an onboard computer, enabling it to capture auroral and airglow imagery in two specific spectral bands (OI 557.7 nm and OI 630.0 nm) through a narrow bandpass filter (3 nm FWHM), as well as visible imagery without a filter. The primary scientific objective of ROKITS is to identify the boundaries of the auroral oval and investigate the diverse shapes of auroras. By combining ROKITS' visible with satellite-based FUV observations, we aim to analyze auroral boundaries in both wavelengths and resolve fine structures within FUV images. Concurrent ground-based auroral observations will further support studies on the evolution of auroral structures. Beyond auroral studies, ROKITS' OI 557.7 nm emission data will contribute to research on atmospheric gravity waves, their role in plasma bubble formation, and the influence of traveling ionospheric disturbances in low- and mid-latitude regions. This approach provides valuable insights into the complex interactions between atmospheric phenomena and space weather.

## AS25-1312

# Effects of collocated auroral emissions on ionospheric characteristics

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Multiple types of auroras may be observed at the same time at different altitudes, with each emission collocated along the same magnetic field line. We analyze observations of collocated auroral emissions recorded by the Transition Region Explorer (TREx)-RGB (red-green-blue) 3 Hz burst all-sky imager (ASI) in Athabasca, AB on 2023-02-27. The ASI shows pulsating aurora activity collocated with a higher altitude red aurora emission for twenty minutes beginning at 12:00 UTC. Pulsating aurora is associated with electron precipitation over a wide range of energies (10s keV-100s keV), whereas red aurora is associated with soft electron precipitation (<1 keV). We use the TREx-auroral transport model (ATM) to investigate the impact of the collocated wave-particle precipitation on the ionosphere. We analyze the changes in conductivity, density, and ionization rates at varying ionospheric altitudes. We discuss the implications of soft precipitation energy input on the pulsating aurora dynamics.

## AS25-1333

# Low latitude auroras during extreme and moderate space weather events from Indian subcontinent

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This study examines low-latitude red auroral sightings over Leh, India, captured by an all-sky camera during moderate to extreme space weather events from 2022 to 2025. To investigate the causes, we analyze in situ particle measurements from space and geomagnetic field data from both satellites and ground-based instruments. We utilize data from NOAA, DMSP, and POES satellites, along with ground magnetometers in auroral and Indian regions. The investigation indicates an equatorward expansion of the auroral oval during geomagnetic disturbances, accompanied by enhanced low-energy particle precipitation could be cause of these Aurora sightings. These results highlight the influence of space weather on auroral dynamics at lower latitudes. The study advocates continuous ground- and space-based monitoring of low latitude is crucial for understanding these events and their role in high- low latitude coupling.

## AS25-1361

# Doppler Shift of Hydrogen Lyman-alpha Line Profiles Produced by Proton Aurora: TIMED/GUVI Observations

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This paper presents our recent effort in understanding of proton aurora using remote sensing data acquired by the global ultraviolet imager (GUVI) instrument on board NASA's TIMED mission. GUVI is a scanning type of imaging spectrograph in the far ultraviolet (FUV) band. The main purpose of GUVI is to provide disc (horizon-to-horizon) images at 5 major wavelengths along the spacecraft track. Occasionally, GUVI can also operate under the spectrograph mode (no scanning) and the entire spectrum is down linked, allowing detailed spectral analysis for calibration purposes. Due to the malfunction of the scanning motor, GUVI has been forced to operate at a fixed looking angle away from the Sun under the spectrograph mode continuously since 2008, thus providing considerable amount of FUV spectral data. However, there has been no effort put into the analysis of the spectral data. Here we will present our analysis result on, for the first time, the Doppler shifted hydrogen (H) Lyman-alpha (Ly-α) line emissions from GUVI. We will explain the algorithm used for extracting and analyzing H Ly-α profiles. As an example, the Mother's day geomagnetic storm on May 10, 2024 is used. Our preliminary result suggests that Doppler redshift, as expected, is common whenever TIMED/GUVI went through the auroral zone, with a redshift of 1–3 Å (~6–30 keV protons). The redshift increases with decreasing latitudes and is larger in the nighttime than daytime sector. This finding is in good agreement with the current knowledge and establishes the capability of GUVI in studying proton aurora.

## AS25-1363

# Connecting stormtime SAR arc variability to mesoscale ring current-plasmasphere evolution via global geospace modeling

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Stable Auroral Red (SAR) arcs are subauroral 630.0 nm emissions commonly observed during geomagnetic storms. Their primary drivers result from overlap between the ring current ions and plasmasphere, thus they provide a means of probing a region of plasma and magnetic flux transport and M-I coupling critical to the overall stormtime geospace behavior. Despite their name, SAR arcs can exhibit high zonal, latitudinal, and temporal variability during geomagnetically-disturbed periods, as well as develop multiple simultaneous arcs separated by less than a degree in latitude. These observations reveal structured and dynamic overlap of the responsible plasma populations, however major open questions remain regarding the extent to which SAR arc variability is driven by structures in the ring current or the plasmasphere, how both global and mesoscale transport processes contribute to this structuring, and what their impacts are on mid-to-low latitude electric fields. In this presentation, we explore these questions using the Multiscale Atmosphere-Geospace Environment (MAGE) global geospace model, leveraging a newly-developed inner magnetosphere model named RAIJU. RAIJU inherits the physical formulations and assumptions of the well-known Rice Convection Model (RCM), while redesigning the core numerics and model framework, enabling much higher resolution in space and energy. This development is crucial for resolving the fine-scale structures associated with SAR arc variability and thermally disparate plasma populations. We find that multiple injections contribute to ring current structuring which can form multiple simultaneous SAR arcs, while undulation-like SAR arc patterns can be formed by the structuring of the plasmapause via dynamic electric fields.

## A27 Advances and Upcoming Developments in Solar and Heliospheric Physics

### AS25-0060

# Energetic Particle Observations measured in the Inner Heliosphere by the Energetic Particle Detector (EPD) on board the Solar Orbiter mission

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One of the key questions that Solar Orbiter aims to address is: How do Solar Eruptions produce energetic particle radiation that fills the Heliosphere? The Energetic Particle Detector (EPD) on board Solar Orbiter is the instrument specifically designed to investigate this topic by measuring solar energetic particles (SEPs) in the inner heliosphere with unprecedented temporal and spatial resolution. Since the mission's launch in February 2020, EPD has provided crucial insights into SEP populations, including their onset times, energy spectra, anisotropies, and compositional characteristics at distances as close as 0.28 au. These observations have shed light on the injection, acceleration and transport processes of SEPs, as well as their relationship with solar flares, jets, coronal mass ejections (CMEs), and the related interplanetary shocks. EPD has also contributed to understanding the variability of SEP events with solar longitude and the role of magnetic connectivity in particle propagation. The unique vantage points of Solar Orbiter have enabled multi-spacecraft studies, providing new perspectives on SEP event evolution in the inner heliosphere. This contribution presents some of the most relevant findings from EPD, highlighting their implications for our understanding of some of the main topics of the solar energetic particle populations in the inner heliosphere.

## AS25-0075

# Science Highlights from the Wide-field Imager for Parker Solar Probe (WISPR)

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The Wide-field Imager for Solar Probe (WISPR) is the imaging instrument on board NASA's Parker Solar Probe, launched in August 2018 with the mission of making measurements of the near-Sun plasma with gradually reduced heliocentric perihelia from 35 Rs in 2018–19 to 9.86 Rs in 2024–25. Here we report the results from the imaging observations of the electron and dust corona taken by WISPR during the first seven years of the mission.

WISPR's unique vantage point from below 15 Rs near its recent perihelia has allowed it to image coronal mass ejections from close up while they are still near the sun, to image near-Sun coronal streamers in the heliospheric current sheet as Parker Solar Probe flies through them, and to detect signatures of the dust depletion zone in the inner heliosphere. In addition, WISPR has detected the circumsolar dust ring near Venus' orbit and the dust trails left behind in the orbits of active asteroid 3200 Phaethon and comet 2P/Encke. We will review these observations and analyses, and discuss prospects for what WISPR may be able to find as it continues its voyage with perihelia at 9.86 Rs.

We acknowledge the work of the PSP operations team. Parker Solar Probe was designed, built, and is now operated by the Johns Hopkins Applied Physics Laboratory as part of NASA's Living with a Star (LWS) program (contract NNN06AA01C). We also acknowledge the work of the WISPR team developing and operating the instrument. WISPR is funded by NASA grant NNG11EK11I.

## AS25-0081

# Particle acceleration and transient processes upstream of planetary bow shocks

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Collisionless shock waves are ubiquitous in astrophysical plasmas, spanning environments from supernova remnants and planetary atmospheres to coronal mass ejections and laboratory experiments. Recognized as efficient particle accelerators, these shocks play a crucial role in explaining the origin of cosmic rays, including ultra-relativistic particles. In this study, we introduce a novel model of reinforced shock acceleration for electrons, integrating in-situ observations from NASA's MMS and ARTEMIS missions along with findings from ESA's Cluster mission. Focusing on Earth's quasi-parallel bow shock, our analysis reveals a suprathermal electron injection threshold and highlights the critical role of shock-generated transients in driving electron acceleration. We demonstrate that HFAs transmitted through the bow shock not only accelerate electrons to relativistic energies upstream but also confine them within downstream transient structures, where elevated compression, possibly via betatron acceleration, leads to further energization. This multiscale process extends far upstream and downstream effectively broadening the acceleration region well beyond the immediate shock transition. By merging theoretical advances in shock physics with a multiscale observational framework, our findings address the longstanding electron injection problem and offer insights applicable to diverse planetary, stellar, and interstellar environments.

## AS25-0228

# Understanding stormtime geospace as a complex, coupled system: Recent progress from the Center for Geospace Storms

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The Center for Geospace Storms (CGS) is a NASA DRIVE Science Center focused on geospace science. CGS is pursuing an understanding of the stormtime geospace as a complex system exhibiting strong coupling across physical regimes, domains, particle populations, and spatiotemporal scales. CGS is tackling this problem via a concerted effort using both data analysis from heterogeneous sources (e.g., in situ, remote sensing and ground-based platforms) and physics-based modeling. In particular, the CGS team is developing the Multiscale Atmosphere-Geospace Environment (MAGE) model that couples all the relevant domains of geospace while doing it at sufficiently high resolution to capture key cross-scale interactions. The CGS's collaborative data-model approach enables discoveries not possible with either data analysis or modeling alone. In this presentation, we discuss recent work from the CGS team concentrating on the stortime plasma sheet, ring current, magnetosphere-ionosphere coupling and the resulting variety of mesoscale auroral forms. Innovative MAGE developments enabling these discoveries will also be discussed including a novel model of energetic particle precipitation in MAGE, based on gray-box modeling of wave-induced particle precipitation, and its applications to high-resolution modeling of the aurora. We also review our recent efforts on developing a new high-resolution (in space and energy) inner magnetosphere model.

## AS25-0230

# How nanoflares heat solar and stellar coronae

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Nanoflares are small explosions that dominate the heating of solar active regions and possibly also the quiet Sun. Their properties (energy, frequency, spatial distribution) determine the thermal distribution of the plasma and therefore the spectrum of emitted radiation. The spatially integrated spectrum (spectral irradiance) has important space weather impacts at Earth and at exoplanets orbiting other stars. I will discuss recent results concerning the properties of nanoflares and their physical origin.

## AS25-0254

# Voyager observations in the local interstellar medium

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The Voyager spacecraft have been in the local interstellar medium (LISM) since 2012 and 2018, with Voyager 1 now about 40 AU past the heliopause. We discuss recent observations and their implications for how the LISM interacts with the heliosphere. Examples are pressure fronts and shocks which produce changes in the magnetic field and density and sometimes generate electron plasma oscillations. Other puzzles are the magnetic field direction, which is rotating away from the predicted LISM direction, and plasma density and magnetic field magnitude, which are higher than LISM expectations.

## AS25-0255

# Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics (SHIELD) DRIVE Science Center

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The heliosphere is an immense shield that protects the solar system from harsh, galactic radiation. Knowledge gaps include the basic shape of the heliosphere, the structure and extent of its tail, the flow pattern and the width of the heliosheath, and the extent of the heliosphere's influence on the local interstellar medium (LISM). Models do not integrate the influences of suprathermal particles, reconnection, turbulence phenomena, and other microprocesses. Microprocesses have spatial scales vastly separate from the global scales but are critical pieces of a heliospheric model and must be parametrized. The transport of cosmic rays and the evolution of PUIs require kinetic transport models that are coupled self-consistently to a global MHD model. The next quantum leap in understanding the heliosphere will be realized by synthesizing knowledge in theory, modeling, and observations to create a comprehensive, self-consistent global model that connects all the physical processes that effect the heliosphere. SHIELD is a NASA DRIVE center with the aim to understand the nature and structure of the heliosphere. The key deliverable is a comprehensive, self-consistent, global model of the heliosphere that explains data from all relevant in situ and remote observations and predicts the radiation environment. To realize our vision and create a new model for the heliosphere, SHIELD will enlist experts on obser- vations, kinetic physics and MHD physics, and high energy particle transport and acceleration physics. In this talk I will describe the ongoing current knowledge gaps and the progresses made in SHIELD.

## AS25-0256

# Observational limits on magnetic helicity transport in emerging flux ropes

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Ideally, the magnetic helicity transport flux through the solar surface could be determined with arbitrary precision by tracking the magnetic field footpoints, assuming infinitely fine observational resolution. However, at the polarity inversion line, the footpoint velocity on the solar surface formally diverges to infinity during flux emergence or submergence. As a result, finite observational resolution creates a "blackout region" in helicity flux estimation near the polarity inversion line, raising the question of how much magnetic helicity is underestimated due to the lack of information within this region. To investigate this, we consider Gold-Hoyle and Lundquist force-free flux ropes emerging through the solar surface. We then estimate the magnetic helicity injected into the solar atmosphere while excluding contributions from the blackout region near the polarity inversion line. If the width of the blackout region is one-tenth of the emerging flux rope's diameter, approximately half of the helicity flux remains unmeasured. Since our calculation assumes infinite observational resolution outside the blackout region, the actual error in the integrated helicity flux estimate may be even larger—especially when small-scale magnetic structures emerge into the solar atmosphere.

## AS25-0276

# Comparing observations of the closely located JUICE and STEREO-A spacecraft during the widespread SEP event of 2024 May 13

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JUICE was launched in April 2023, and it is now in its cruise phase to Jupiter, where it will arrive in July 2031. JUICE carries a RADiation hard Electron Monitor (RADEM) to measure protons, electrons, and ions, detecting particles coming from the anti-Sun direction. On 2024 May 13, a large solar energetic particle (SEP) event took place in association with an eruption close to the western limb of the Sun as seen from Earth. Providentially, at that time JUICE was very close located to STEREO-A.

We analysed the interplanetary context through which the particles propagated. We studied the proton anisotropies measured by near-Earth and STEREO-A and consider the isotropic period at the decay phase of the SEP event to compute the proton accumulated spectrum. We considered STEREO-A spectral fitting as the particle environment measured by JUICE and estimated the differences in the proton flux measured by JUICE in comparison with the fitting.

The proton spectral indices measured by JUICE and STEREO-A are comparable. The proton fluxes measured on the effective energy channels of 6.9 MeV, 13.3 MeV, 21.6 MeV, and 31.2 MeV by RADEM agree, with a deviation of less than 15%, with STEREO-A measurements This analysis demonstrates that the RADEM instrument aboard JUICE is a valuable tool for measuring SEP events in the heliosphere.

## AS25-0310

# Voyager and Cassini Mission Discoveries on the Physics of the Global Heliosphere

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The combination of in-situ particle and field measurements, particularly the >28 keV ions from the Low-Energy Charged Particle (LECP) detector on Voyager1&2, have established *"ground truth"* to the ~5–55 keV Energetic Neutral Atom (ENA) images from Cassini/INCA, and have been essential to address longstanding, fundamental questions, such as the properties and acceleration of low energy ions and Anomalous Cosmic Rays (ACRs) inside the heliosheath, the effects of the solar cycle through the outward propagating solar wind, the force balance and interaction with the Very Local Interstellar Medium (VLISM) that controls the shape and size of our solar bubble, and many more. The solar wind plasma is confined between the termination shock and the heliopause (HP), forming a heliosheath that exhibits diamagnetic behavior and interacts directly with the strong interstellar magnetic field. Recent measurements have revealed the complexity of this interaction: the V1 crossing of the HP was associated with the discovery of a radial inflow of low energy ions inside the heliosheath for ~9 AU before the HP, consistent with the identification of two interstellar flux tubes that had invaded the HS with strong anticorrelations in GCRs. The HP crossing revealed a radial outflow of ions for at least 30 AU past the HP, whereas the synergistic use of in-situ magnetic field, electron density and low energy ion observations, suggested that V1 may have entered a new region in the VLISM since (at least) the year 2021 at ~151 au, progressively developing characteristics akin to the pristine interstellar medium.

## AS25-0340

# ’3D analysis of white-light tracers of the solar wind: kinematics and dynamics’

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One of the common types of mesoscale density enhancements detected in white-light data are blobs. The advantage of multi-view point observations is that it permits us to calculate the deprojected position of these structures in space. In this investigation we used the coronagraph combinations of C2 & C3 (LASCO/SOHO) and COR2 A & B (SECCHI/STEREO), obtaining a combined field-of-view from 3 to 15 solar radii. One of the most interesting applications of the ‘real’ position of blobs is to study the dynamics of the ‘blob-solar wind’ system, or how the blob interacts with the surrounding solar wind. In this work we present the results of the analysis of two dynamic models using the deprojected morphology and kinematics of blobs.

## AS25-0456

# Evolution of CMEs in interplanetary space observed with Parker Solar Probe and Solar Orbiter

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Coronal mass ejections (CMEs) are massive ejections of plasma and magnetic fields from the Sun that play a crucial role in space weather dynamics. The Parker Solar Probe (PSP) and Solar Orbiter (SolO) missions, with their complementary orbits and advanced instruments, provide an unprecedented opportunity to observe CMEs from different heliocentric distances and perspectives. By combining data from multiple spacecraft from in-situ measurements and remote sensing observations, we can study the evolution of CMEs and their interactions with the surrounding solar wind.

In particular, the high-resolution images acquired by PSP and SolO near the Sun allow the study of CME substructures such as blobs and their role in interaction processes with the solar wind. But also, interactions with other large-scale solar wind structures (other CMEs, co-rotating interaction regions, or the heliospheric current sheet) can be studied in even greater detail. These can significantly distort CMEs, alter their trajectories, and change the evolution of their magnetic structures. This might either weaken or amplify their impacts on planets, hence, posing a challenge for modeling. Ultimately, these studies contribute to a deeper understanding of Sun-Earth interactions.

## AS25-0493

# Science discoveries with SO/PHI, the Polarimetric and Helioseismic Imager on Solar Orbiter

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The SO/PHI instrument, flying on the ESA/NASA deep space mission Solar Orbiter, is a vector magnetograph that records both full-disk and high-resolution magnetic, brightness and velocity data. The unique orbit of Solar Orbiter allows SO/PHI to observe the Sun from outside the Sun-Earth line, making it the first magnetograph with this capability. Over Solar Orbiter's nominal mission phase SO/PHI has produced exciting results on topics ranging from the evolution of active regions, the velocity structure of granules, the 180-degree ambiguity in the transverse magnetic field, the Wilson depression of sunspots, waves in magnetic features, helioseismic far-side imaging, facular brightening, and many more.

And this is just the beginning. The most exciting part of the odyssey of SO/PHI still lies ahead, the high latitude phase of the mission, during which the spacecraft leaves the ecliptic plane and gradually moves to higher latitudes, allowing PHI to capture the first clear images of the magnetic field and flows at the solar poles.

## AS25-0497

# Reversal of the tangential component of the solar wind velocity and its possible relation to switchbacks

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Tangential component of the solar wind velocity is positive (co-rotating) above Sun surface but it turns its sign at about 0.2 AU. The negative value increases toward 0.3 AU and then gradually relaxes to zero at larger distances. Since the intervals of a large negative tangential velocity component exhibit also enhanced cross-helicity, outward propagating Alfven waves were suggested as the most probable source of the observed deviation. The weak point of this suggestion is that the waves would affect the solar wind velocity in all directions with the same probability but no change of the normal velocity component is observed. For explanation of this caveat, we use the newly created database of switchbacks observed by PSP and analyze behavior of three ion components – proton core, proton beam and alpha particles within time intervals corresponding to switchbacks. Since the relative velocities of these components are comparable with the bulk velocity of the proton core, we calculate the velocity in the deHoffmann-Teller frame that was suggested as a proper solar wind velocity. Results of our analysis suggest interchange reconnection of closed lines of coronal loops with the open lines from nearby coronal hole as a most probable driver of the switchbacks as well as reversals the tangential component of the solar wind velocity. However, this type of reconnection is expected at the source regions of the slow wind whereas the negative tangential velocity component was observed in the fast wind and we discuss a scenario that can explain this discrepancy.

## AS25-0519

# Unveiling the solar corona: key science discoveries from Metis on Solar Orbiter

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Metis, the coronagraph on-board ESA/NASA's Solar Orbiter, has provided unprecedented observations of the solar corona during its five years of operation. By simultaneously imaging the corona in visible and ultraviolet light, Metis enables the study of the processes driving the solar wind as well as the large-scale dynamics of the solar atmosphere.

This talk will present a brief summary of the scientific achievements so far, the available data, and how these findings contribute to our understanding of heliospheric physics. Additionally, upcoming developments and future observational opportunities with METIS will be discussed, particularly in light of the spacecraft's forthcoming out-of-ecliptic observations, which will offer a unique perspective on the Sun's polar regions.

## AS25-0566

# First results of the ASPIICS coronagraph aboard the PROBA-3 mission

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PROBA-3 is an ESA mission dedicated to the in-flight demonstration of precise formation flying techniques and technologies, and also a Mission of Opportunity in the ESA Science Programme. It was launched on 5 December 2024. The PROBA-3 mission consists of two small satellites placed in a highly elliptical orbit around the Earth. The two satellites will fly in a precise formation, producing a very long baseline solar coronagraph called ASPIICS (Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun). One spacecraft carries the optical telescope, and the second spacecraft carries the external occulter of the coronagraph. The inter-satellite distance of around 144 m will allow observing the inner corona in eclipse-like conditions, i.e. close to the solar limb and with very low straylight. Scientific objectives and first results of ASPIICS will be presented and discussed.

## AS25-0876

# Why are solar filaments filamentary?

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Solar prominences exhibit ribbon-like structures composed of fine, thread-like filamentary substructures. They are generally believed to form through the cooling and condensation of hot coronal plasma via thermal instability. Observations frequently show sub-Alfvénic counter-streaming flows within prominences, likely aligned with magnetic field lines. Motivated by these observations, we performed a linear stability analysis of magnetized plasmas with shear flows. Our analysis reveals that the eigenfunctions of the thermal condensation modes exhibit singular behavior, resembling delta functions. However, this singularity disappears if the shear velocity is less than 10^{−4} times the Alfvén speed. We have derived a second-order ordinary differential equation for a single variable and found that the coefficient of its second derivative term vanishes at locations where the singular eigenfunctions appear. This suggests that the formation of ribbon- and thread-like structures is a natural consequence of thermal instability in magnetized shear flows.

## AS25-1016

# Turbulence diagnostics for scale-by-scale accuracy of solar wind forecasts

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The non-linear dynamics of the solar wind cover multiple decades of scales. These scales are not independent and are linked by turbulent processes. For instance, the energy will cascade from the largest scales determined by the dynamic and structure of the corona, to the smallest where kinetic dissipation and heating of the plasma occur. Mesoscale structures of size superior to the minute can be induced or affected by the turbulent cascade of energy or can generate a cascade. They have the right size to interact quasi-stationarily with the magnetosphere. However, are they well reproduced in space weather forecasts? We question the scale-by-scale accuracy of solar wind forecasts using turbulent-state diagnostics. These forecasts are obtained from the analogue ensemble methodology applied to L1 measurements. We will discuss the implications of our results for space weather forecasting.

## AS25-1063

# The first low frequency radio telescope on the Moon under NASA's Commercial Lunar Payload Services Program

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The first NASA-funded radio telescope on the Moon was launched onboard Intuitive Machine's Odysseus lander and was deployed on the Moon on 2024 February 22. The telescope consisted of four monopole antennas designed to study the low-frequency radio sky and the local lunar plasma environment. The radio instrument is named ROLSES (Radio-wave Observations of the Lunar Photo-electron Sheath) and was one of the first payloads developed under NASA's Commercial Lunar Payload Services (CLPS) program and to reach the surface of the Moon. Odysseus had a "hard" soft-landing, breaking one of its legs, and was tipped over onto the lunar surface at an angle of ≈30◦. Nevertheless, we were able to deploy ROLSES antennas and were able to obtain some data. One of the four monopole antennas deployed unexpectedly enroute due to excessive solar flux falling on the deployment mechanism and overheating it. We were able to operate the telescope both enroute and on the surface obtaining data only for tens of minutes. With this data, it was possible to observe signals from ground transmitters above the ionospheric cutoff. I present these observations and future plans for the improved version of the ROLSES instrument to be flown on Firefly Aerospace's Blue Ghost lander.

## AS25-1135

# Solar Wind Science Discoveries with BepiColombo

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BepiColombo, the joint ESA/JAXA mission to Mercury, was launched in October 2018 and is scheduled to arrive at Mercury in November 2026 after a 8-year cruise. Like other planetary missions, its scientific objectives focus mostly on the nominal, orbiting phase of the mission. However, due to the long duration of the cruise phase covering distances between 1.2 and 0.3 AU, the BepiColombo mission has been able to outstandingly contribute to characterise the solar wind and transient events encountered by the spacecraft, as well as planetary environments during the flybys of Earth, Venus, and Mercury, and contribute to the characterization of the space radiation environment in the inner Solar System and its evolution with solar activity. In this talk, we provide an overview of the cruise observations of BepiColombo, highlighting the most relevant science cases, with the aim of demonstrating the importance of planetary missions to perform cruise observations, to contribute to a larger understanding of Space Weather in the Solar System, and in turn, increase the scientific return of the mission.

## AS25-1139

# Status and Initial Results from NASA's Polarimeter to UNify the Corona and Heliosphere (PUNCH) Mission

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The Polarimeter to UNify the Corona and Heliosphere (PUNCH) is a NASA Small Explorer mission to understand the corona and solar wind as parts of a single, unified system. Flight assets comprise four satellites in dawn/dusk Sun-synchronous low Earth orbit, each supporting one deep-field polarizing visible-light camera. One Narrow Field Imager (NFI) and three Wide Field Imagers (WFIs), with matched optical characteristics and exposure sequences, collect deep-field images as a single wide-field camera, to track the solar wind from the top of the corona through interplanetary space. Ground assets include the most sophisticated ground pipeline for any NASA Explorer mission, to merge the separate data streams into a single field of view with photometric accuracy in the 0.01% range. Launched on 2025 March 11, the four spacecraft underwent 90 days of commissioning. At this meeting, we present status of the mission and initial results from the first 30 days of science operations.

## AS25-1154

# Advances in Our Understanding of Solar Dynamo from Continuous Helioseismic Observations on SOHO/MDI and SDO/HMI

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Helioseismic observations performed since 1996 from the Solar and Heliospheric Observatory (SOHO) Michelson Doppler Imager (MDI) and Solar Dynamic Observatory (SDO) Helioseismic and Magnetic Imager (HMI) provided continuous monitoring of the interior structure and dynamics. They substantially advanced our understanding of solar dynamo, the basic mechanism of the magnetic activity cycles. In particular, the observations of solar-cycle variations of the internal differential rotation revealed patterns of zonal acceleration that originate at the bottom of the convection zone and migrate in radius and latitude, forming "extended" 22-year cycles. These patterns correspond to dynamo waves predicted by theoretical models. In addition, helioseismic observations revealed the extended cyclic variations of the meridional circulation, which also agrees with the dynamo theory. We discuss current challenges, unsolved problems, and upcoming developments in observations and modeling to study the physical processes inside the Sun.

## AS25-1190

# Linking 3D realistic modeling of the Sun's subsurface dynamics with observations

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Understanding the influence of turbulent convection and rotation on the dynamics and structure of the solar interiors is essential for many problems related to solar activity, such as the formation of differential rotation, meridional circulation, and others. The realistic 3D radiative hydrodynamics simulations of the Sun reveal the self-formation of the differential rotation and meridional flows. The resulting 'ab initio' models obtained for different rotation rates and latitudes allow us to get insights into details of the near-surface shear layer and improve our understanding of turbulent properties of solar convection. The simulations reveal the formation of the leptocline (a shallow 10 Mm deep substructure of the near-surface shear layer), which is associated with enhanced anisotropic overshooting-type flows into a less unstable layer between the H and HeII ionization zones. In addition, the simulations reveal a temporal evolution of the meridional and azimuthal flows in the solar models and lead to a paradigm shift in our understanding of how properties of turbulent convection change with depth in the convection zone. We compare the solar models with helioseismic inferences and demonstrate potential improvements in the different data techniques, such as time-distance and ring diagram analysis. Finally, we will present the most recent results for modeling high-latitude regions in support of the current space missions (SDO, Hinode, and Solar Orbiter) and future polar missions.

## AS25-1304
# Global Solar Flare Modeling

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Developing a self-consistent global model of solar flares remains impractical due to the vast difference — more than ten orders of magnitude — between the time and length scales of kinetic and fluid processes. These processes are entangled in localized regions where magnetic reconnection occurs, including null points and pockets of non-ideal plasma. Magnetic reconnection plays a key role in particle acceleration and heating while also changing the global field's topology. Although kinetic simulations effectively describe reconnection-driven particle acceleration, they are limited to short timescales and small regions compared to the lifetime and sizes of flares. Conversely, magnetohydrodynamics (MHD) models track the large-scale evolution of the magnetic field, such as current sheet formation and bulk motion, but exclude particle motion and its feedback on the fields.

This talk will present recent efforts to bridge the theoretical gap between these scales by linking specialized models into a self-consistent framework. MHD simulations of the formation of the flare current sheet and arcade loops provide the background conditions for targeted models. The nonthermal output of particle acceleration and heating models at the current sheet serves as input for transport models describing an injected particle beam as it evolves along the flare arcade legs and deposits energy at the solar surface. Finally, the predicted high-energy emissions can then be compared to observations.

Challenges remain, but this multi-scale approach offers new insights into flare dynamics. This talk will discuss both recent progress and ongoing obstacles in the quest for a comprehensive solar flare model.

## AS25-1320

# Parker Solar Probe: From Exploration to Paradigm-Shifting Discoveries

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Parker Solar Probe: From Exploration to Paradigm-Shifting Discoveries

The Parker Solar Probe mission has been revolutionizing our understanding of the Sun for nearly half a solar cycle, providing unprecedented insights into its dynamic atmosphere. Having completed 22 of its planned 24 orbits during the mission's prime science phase, the spacecraft continues to deliver data of unmatched quality, captivating both the global scientific community and the public. Parker Solar Probe has already yielded paradigm-shifting discoveries, cementing its status as one of the most successful heliophysics missions to date. With the spacecraft and its instruments performing exceptionally well, the mission's future beyond the prime science phase looks exceedingly promising. I will provide an overview the mission's remarkable achievements and explore its potential as we move into the declining phase of solar cycle 25 and beyond.

## AS25-1322

# Investigating the origin of the fast solar wind by linking remote-sensing and in-situ measurements from dedicated Solar Orbiter observing campaigns

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We will present the results of "Fast Solar Wind" SOOPs (Solar Orbiter Observing Plans) that we led and co-led in October 2023 and April 2024. Their scientific goal was to investigate the origin of the fast solar wind by relating coronal holes observed remotely to the fast solar wind measured in situ. We combined low-latency images by EUI (Extreme Ultraviolet Imager) onboard Solar Orbiter, Earth-perspective observations by the Solar Dynamics Observatory, and PFSS (Potential Field Source Surface) models to decide the target for remote-sensing observations, which were low-latitude coronal holes. We combined the analysis of the in-situ measurements with remote observations by SPICE (Spectral Imaging of the Coronal Environment), EUI including high-cadence measurements by HRI (High Resolution Imager), and PHI (Polarimetric and Helioseismic Imager). Coordinated observations for spectroscopy and/or imaging from Earth were also conducted by Hinode and IRIS (Interface Region Imaging Spectrograph), allowing us to explore different layers of the Solar atmosphere including the chromosphere, the transition region, and the lower to middle corona. During the 2024 SOOP, we could also exploit a radial alignment between Solar Orbiter and PSP, which measured in situ the same stream of plasma at different heliocentric distances. We will show and discuss how we are (and will be) exploiting this vast collection of combined observations with improved models of the solar wind footpoints performed a posteriori (e.g., using MHD simulations) to locate the source regions of the probed fast wind and thus identify its origin and release mechanisms.

## AS25-1371

# Thermal and Magnetic Properties of Coronal Pseudostreamer and Helmet Streamer Cavities

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Coronal cavities are three-dimensional oval-shaped structures that surround prominences and are embedded in streamers. Cavities have significant substructure, including flows and variation in temperature. In this study, we use multiwavelength observations from SDO/AIA to construct Differential Emission Measure (DEM) maps of these structures to study their thermal properties. We also use SDO/HMI magnetograms and NLFFF models to obtain their magnetic field properties and reconstruct their 3D topology. We compare cavity physical parameters between pseudostreamers and helmet streamers. Understanding the physical characteristics of streamer cavities can provide key information on the processes involved in their evolution and stability.

## AS25-1390

# Voyager Discoveries at the Edge of the Heliosphere: Observations and Modeling of Shocks, Waves, and Turbulence

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The Voyager spacecraft (V1, V2), humanity's farthest-reaching missions, have provided unprecedented insights into the interaction of the solar wind with the local interstellar medium (LISM). Remarkably, both spacecraft continue to send science data to Earth. In the inner heliosheath—the region between the termination shock and the heliopause—the solar wind is subsonic and energetically dominated by suprathermal pickup ions. The very local ISM (VLISM), the LISM portion perturbed by the heliosphere, is partially ionized and collisional. Charge exchange provides a fundamental coupling mechanism between the solar wind and the LISM. These processes slow down interstellar atoms, producing secondary ions that quickly decelerate, creating a region of compressed plasma pierced by the interstellar magnetic field draped around the heliopause.

Voyager observations revealed that the VLISM is not a uniform, quiescent environment but rather a dynamic region characterized by shocks, turbulence, and waves, primarily driven by heliopause motion and therefore heavily influenced by solar activity. These perturbations have been detected out to 160 AU from the Sun but may survive to far greater distances. Voyager in situ observations are critical for inferring the unperturbed LISM properties. However, any analysis of these phenomena requires extensive, data-driven, 3D modeling. Here we present the most recent Voyager discoveries, and discuss open challenges in their explanation and interpretation. We discuss the Voyager data to highlight the evolution of compressible turbulence. Our global modeling efforts demonstrate the role of the solar cycle in producing the major pressure fronts and large-scale compressions in the VLISM.

## AS25-1396

# Evolution of CME Magnetic Field Research: From Simplified Models to Complex Topologies

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Coronal mass ejections (CMEs) represent complex magnetized plasma systems with intricate magnetic field structures that have been the subject of extensive research over the past four decades. The traditional paradigm, characterized CMEs as highly twisted circular cross-section magnetic flux ropes inspiring numerous fitting and reconstruction techniques that aimed to provide three-dimensional visualizations from one-dimensional time series measurements obtained in situ. However, recent advancements in observational capabilities, including multi-point measurements and remote-sensing observations, combined with more sophisticated physical models and numerical simulations, have revealed significant limitations in this simplified paradigm. These developments demonstrate that while the highly twisted flux rope model explains certain CME signatures, it fails to capture the true complexity of magnetic field structures observed in many cases.

The magnetic topology of CMEs extends beyond simple twist configurations. Quantitative analysis using three-dimensional simulations shows that a significant portion of magnetic helicity near 1AU is distributed across different forms, including writhe and mutual helicity, rather than being concentrated solely in twist.

In this work we present a review of over four decades of research on the magnetic field structure of CMEs and its implication on future fitting techniques. We also present a technique using measures of field line topology to analyze the magnetic field of CMEs at 1 AU.

## AS25-1420

# From multi-decadal solar wind modelling to real-time forecasting, and on probing solar wind away from the ecliptic plane

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The solar wind is an uninterrupted flow of highly ionised plasma that streams from compact sources at or near the Sun, accelerates across the low solar corona, and expands into the whole interplanetary space. The physical properties of any wind streams thus reflect the characteristics of their source regions and those of the extended zones of the corona they cross, and are affected by the time-varying strength and geometry of the global background magnetic field. I will discuss the spatial distribution of solar wind sources and relate them to the properties of the interplanetary wind by means of an extended sequence of data-driven 3D simulations that cover more than two solar activity cycles. Similarly, I will relate magnetic connectivity jumps with solar wind plasma signatures, and discuss their occurrence frequency and amplitudes at different epochs of the solar cycle, and the differences that will arise when sampling the solar wind off the ecliptic plane. I will also address some of the main challenges related to the implementation and validation of these models, as well as the pernicious issues that stem from the lack of observables between the two boundaries of the Sun–Earth system.

## AS25-1426

# Investigating the evolving large-scale structure of the corona and heliosphere using synthetic observables

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The environment shaped by the Sun—the heliosphere—is extremely dynamic, its structure being constantly shaped and altered by the solar activity over multiple time scales. Given the sparsity of observational (both remote-sensing and in-situ) data of the solar atmosphere and interplanetary space, magnetohydrodynamics (MHD) models are often employed to evaluate the global structure of the heliosphere and to contextualise available spacecraft measurements. Amongst these, simulations that employ time-dependent boundary conditions are best suited to investigate the status of the heliosphere throughout a certain interval of interest. We recently developed a near-real-time, data-assimilative MHD model using the MAS code to predict the solar corona's appearance during the 2024 total eclipse, simulating a consistently evolving corona and heliosphere over 32 days.

An interesting avenue to pursue in the post-processing phase of a simulation is represented by the generation and analysis of synthetic data "as if they were real observations". These include, e.g., remote-sensing imagery at extreme ultra-violet wavelengths and/or in white-light as well as in-situ measurements generated from spacecraft (real or synthetic) trajectories. In this presentation, we first provide an overview of synthetic data of the solar corona and heliosphere based on the PSI 2024 eclipse simulation. We then highlight a series of comparisons between the model's data and their corresponding observations over the eclipse interval and discuss the advantages of combined analyses uniting "MHD model quantities" (such as 3D cubes and magnetic field lines) with the synthetic remote-sensing and in-situ observation for a more detailed context and deeper understanding of the corona–heliosphere system.

## AS25-1431

# Properties of coronal slow and fast propagating disturbances under different levels of solar activity

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Many aspects of the nascent slow solar wind near the Sun are poorly understood, including the source and formation of small-scale propagating density features. Recent analysis of small-scale propagating disturbances revealed by advanced image processing techniques in extreme ultraviolet and white light observations showed, for the first time, plane-of-sky velocity profiles starting from 1.5 solar radii. This analysis highlighted the possible existence of two classes of propagating disturbances which ultimately converge to typical slow solar wind velocity profiles estimated by small-scale structures in the high corona. The two classes of features are differentiated by their speed in the low-middle corona: slow features start at speeds of about tens of km/s and sharply accelerate around 3 solar radii; fast features start with speeds of hundreds km/s and gradually accelerate to slow solar wind speeds. These results were obtained during a period of solar minimum. We have now expanded this study and performed a similar analysis on multiple events during different phases of Solar Cycle 24. Here, we present a comparison of properties of these propagating disturbances in terms of their formation locations and kinematic properties capitalizing on both ultraviolet and white light observations. By leveraging the rare occasions of uninterrupted field of view from the sun surface to the high corona, the properties of these propagating disturbances can help us improve our understanding of the formation and acceleration of the slow solar wind.

## AS25-1433

# Solar Interior: New Insights from Global Inertial Modes

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Recent maps of horizontal flows near the solar surface have revealed global oscillations of the Sun in the inertial frequency range, providing a new way to probe the solar interior alongside the traditional acoustic modes, which have long been used to study internal structure and large-scale flows. The inertial modes that we observe are all retrograde in the Carrington frame of reference. Advances in modelling these modes combine linear eigenmode analysis of the differentially rotating convection zone with nonlinear numerical simulations, revealing their diagnostic potential and their role in shaping solar dynamics. The modes are particularly sensitive to the deep convection zone, offering insights into poorly constrained properties, such as the superadiabaticity, the turbulent viscosity, and the latitudinal entropy gradient. A key finding is the strong interaction between high-latitude inertial modes and the latitudinal differential rotation.

## AS25-1451

# The Solar Multimessenger era: Solar Orbiter & PSP

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Solar Orbiter and Parker Solar Probe are encounter missions in the near Sun environment probing in-situ plasma conditions resulting from processes and interactions in the solar atmosphere. Aided by remote sensing observations from space and ground-based observatories of these processes, we have discovered a wealth of cause-effect relations linking what happens on the Sun to heliospheric consequences. These links provide clues that expand from the creation, release and acceleration of the solar wind to the eruption and propagation of coronal mass ejections, the most impactful phenomena determining space weather conditions in the heliosphere. These investigations require enormous coordination efforts of instrument and scientific teams that will continue into the next phases of the two missions, including the out of the ecliptic part of the Solar Orbiter mission. The addition of the fully commissioned Daniel K Inouye Solar Telescope, able to observe the magnetism of the solar corona, the results from the highly successful third SUNRISE-balloon flight, and the ESA-led Vigil mission from the vantage point at L5 will further enhance our understanding of the magnetic connectivity between the Sun and the Earth in the coming years.

## AS25-1462

# Radio imaging observations of coronal mass ejections

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Coronal Mass Ejection (CME) observations in radio at meter to decimeter wavelengths are particularly challenging. Spatial scales during CME related phenomena seen in radio vary widely from loop gyro-synchrotron and synchrotron sources extending several solar radii, to very narrow bursty emissions that will be close to the minimum size defined by scattering in the solar atmosphere. Temporal scales pose also a challenge: many outbursts require better than 1 second time resolution and the typical eruptive event develops over a time interval less than 10 minutes. Since CMEs initiation can not yet be predicted dedicated instruments capable of very fast imaging are required: scheduled observations during short periods are likely to fail to observe major events. Then there is the immense dynamic range: during major outbursts the flux can be dominated by several narrow sources with extreme brightness temperatures that can differ by many orders of magnitude. These bursts can then obscure each other and the wider features of the Sun meaning that even a very sensitive instrument may not be able to detect all sources present. Finally instruments need to cover a very large spectral window but with good spectral resolution: some sources will be essentially stationary in their frequency range, others will show drifts of hundreds of MHz per second, while shock associated features will show drifts about two orders of magnitude lower. This presentaion will make an overview of the most relevant observations, recent advances, and exciting developments expected in the near future for CME observations in radio.

## AS25-1477

# The future of Solar active region observation

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Solar active regions are transient phenomena on the Solar atmosphere characterized by strong magnetic fields. These fields manifest as sunspots, plages, and associated structures. Active regions also play an important role in the dynamic breeding grounds for solar flares and coronal mass ejections (CMEs). A comprehensive understanding of these regions requires multi-wavelength observations spanning from the photosphere, where magnetic fields emerge, to the corona.

The next generation of solar telescopes is pushing the boundaries of observational capabilities. With its unparalleled spatial resolution and adaptive optics, the Daniel K. Inouye Solar Telescope (DKIST) and the future European Solar Telescope (EST) enable detailed studies of magnetic field structures, plasma flows, and wave phenomena in the photosphere and chromosphere, revealing the fundamental processes that drive active region evolution. Simultaneously, the Parker Solar Probe and Solar Orbiter, and SDO, among others, provide in combination crucial in-situ measurements and remote sensing observations from the photosphere up to the corona and the heliosphere, allowing us to trace the origins and acceleration of the solar wind, energetic particles, and CMEs closer to the Sun than ever before. These missions and advanced state-of-the-art computational tools provide a wealth of data that allows researchers to unravel the complex interplay between magnetic fields, plasma, and energy release within active regions.

In this presentation, I will emphasize the pivotal role of these observations, from the photospheric magnetic field vector measurements, chromospheric spectral emissions, and coronal plasma diagnostics, in characterizing the intricate structure, dynamic evolution, and energy release mechanisms within active regions.

## A28 Turbulent energy dissipation and particle dynamics in the solar wind and the solar corona

### AS25-0024

# Formation of a magnetic coherent structure via the merger of two plasmoids in solar supergranular turbulence

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We discuss the intensification of electromagnetic energy flux (Chian et al. MNRAS 2023) and formation of a magnetic coherent structure in a vortex expansion–contraction interval (Chian et al. MNRAS 2024), resulting from the merger of two plasmoids driven by a supergranular vortex observed by Hinode in the quiet-Sun. Strong vortical flows at the interior of vortex boundary are detected by the localized regions of high values of the instantaneous vorticity deviation, and intense current sheets in the merging plasmoids are detected by the localized regions of high values of the local current deviation. The spatiotemporal evolution of the line-of-sight magnetic field, the horizontal electromagnetic energy flux, and the horizontal electric current density is investigated by elucidating the relation between velocity and magnetic fields in the photospheric plasma turbulence. A local and continuous amplification of magnetic field from 286 G to 591 G is detected at the centre of one merging plasmoid during the vortex expansion–contraction interval of 60 min. During the period of vortex contraction of 22.5 min, the line-of-sight magnetic field at the centre of plasmoid-1 (2) exhibits a steady decrease (increase), respectively, indicating a steady transfer of magnetic flux from plasmoid-1 to plasmoid-2. At the end of the vortex expansion–contraction interval, the two merging plasmoids reach an equipartition of electromagnetic energy flux, leading to the formation of an elongated magnetic coherent structure encircled by a shell of intense current sheets. Evidence of the disruption of a thin current sheet at the turbulent interface boundary layer is presented.

## AS25-0117

# Emergence of a Characteristic Scale in the Inertial Range of Near-Sun Alfvénic Solar Wind Turbulence: Role of Switchbacks

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Alfvénic solar wind turbulence is typically characterized using spectral and structure function analysis in three different ranges of scales. At large scale, a 1/f spectrum suggests an energy reservoir of uncorrelated fluctuations. This is followed by an inertial range where spectra and intermittency broadly compatible with Kolmogorov or Iroshnikov-Kraichnan phenomenology are present, with substantial anisotropy. Finally, a sub-ion scale range shows steeper spectral decay, limited or no intermittency, and emergence of Hall effects, plasma instabilities, and wave particle interactions. Recently, near-sun Parker Solar Probe observations suggest that one further characteristic scale exists within the inertial range, which is thus formed by two sub-ranges whose extent evolves radially as the solar wind expands. Those ranges are characterized by Iroshnikov-Kraichnan and Kolmogorov spectra at larger and smaller scales, respectively. The break between the two regions seems to be connected with the presence of patches of switchback. Here we show evidence for such double inertial range and discuss its possible origin from an observational point of view.

## AS25-0144

# Electron dynamics from the solar corona into the turbulent solar wind

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Electrons are a subsonic plasma species in the solar wind. Their kinetic behaviour is—to a much greater extent than the proton behaviour—the result of an interplay between global properties of the heliosphere and local plasma processes. The global properties of the heliosphere include the interplanetary electrostatic potential, the large-scale interplanetary magnetic field, and the density profile of the plasma. The local plasma processes include collisions, wave-particle interactions, and turbulence. Through this interplay, the electron distribution function develops interesting kinetic features that are observable in situ. In addition to a quasi-Maxwellian core, the distribution exhibits suprathermal populations in the form of the strahl and halo components as well as cut-offs due to loss effects in the interplanetary potential.

We discuss the processes that shape the electron distribution in the solar wind, the interaction of electrons with local structures such as turbulence, waves, and magnetic holes, and the impacts of these structures on the global electron transport in the heliosphere. The regulation of the electron heat flux is of particular interest in this context. We support these results with observations from Solar Orbiter and Parker Solar Probe.

## AS25-0164

# Temperature reducing shocks in turbulent coronal magnetic reconnection

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Shocks are an intrinsic part of compressible turbulence and readily form in magnetohyrodynamic systems at reconnection sites, and are seen as a net contributor towards heating in the solar corona due to adiabatic and dissipative heating in and around shocks. However, in coronal conditions, optically-thin radiative losses efficiently remove thermal energy from the system, affecting the energy redistribution. Here I present the first results to demonstrate that in coronal shocks, the radiative losses can far exceed the shock heating, leading to shocks that reduce the temperature of the plasma, i.e., shocks can cool the solar corona, rather than heat it. I first present the analytical proof of temperature reducing shocks in coronal conditions, then perform turbulent simulations of magnetic reconnection. Shock properties are extracted using the ShockID code and it is found that ~40% of detected shocks are temperature reducing and can lower the temperature by an order of magnitude. This unexpected result forces us to rethink the role of shocks in the thermal evolution and energy redistribution of the solar corona.

## AS25-0231

# The Interaction of Turbulence with Collisionless Solar Wind Shocks

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The interaction of turbulence with shock waves is a classical problem although it has only recently begun to attract attention in the context of collisionless shocks in the solar wind. Using a combination of theory, numerical simulations, and observations, we have undertaken an extensive investigation of the interaction of magnetized turbulence with collisionless shocks in the solar wind. The nature and character of turbulence is critical to the energization of particles at shock waves throughout the universe. We will present two recent theoretical approaches to the transmission and generation of turbulent fluctuations at a collisionless shock before discussing supporting simulations of the theory. We will conclude with an extensive set of observations using a variety of different techniques, including a recently developed extension of a linear mode decomposition analysis, to illustrate the effectiveness of the theory in explaining a range of observed features downstream of interplanetary shocks.

## AS25-0342

# Interplanetary shock as a source of upstream and downstream waves

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Observational and theoretical studies as well as simulations have shown that interplanetary (IP) shocks are associated with different types of waves that can exist in their upstream and downstream regions. The nature of upstream and downstream wave packets depends upon the shock strength expressed by the Mach number and the geometry described by the angle between the shock normal and upstream magnetic field. Low-Mach number, weak shocks are the result of a balance between the nonlinear steepening and either dissipation due to some anomalous processes or wave dispersion. High-frequency (several Hz) wave packets in the upstream region of quasi-perpendicular shocks are observed in fast magnetic field data and provide a strong evidence that these shocks have magnetosonic whistler precursors with frequencies up to 7 Hz. On the other hand, low-frequency waves (up to 1 Hz) are more frequently registered in the downstream region behind the shock. We present the analysis of low-Mach number and low-beta nearly perpendicular shocks with waves with similar upstream and downstream frequencies in the spacecraft frame. These waves propagate along the magnetic field in upstream region whereas perpendicular propagation is preferred in downstream. A deeper analysis shows that upstream and downstream frequencies are identical in the shock frame of reference.

## AS25-0362

# Relation of the magnetic field and ion velocity spectra in the solar wind

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The paper analyzes the relation between power spectra of solar wind velocity and magnetic field fluctuations in the frequency range around the break between inertial and kinetic scales. The extensive statistical study uses ion velocity measurements of Bright Monitor of Solar Wind (BMSW) on board Spektr-R with a time resolution of 32 ms complemented with 0.1 s magnetic field observations from Wind propagated to the Spektr-R location and compare them partly with observations of Solar Orbiter and Parker Solar Probe closer to the Sun. We concentrate on the ion kinetic scale and investigate the role of parameters like the fluctuation amplitudes of parallel and perpendicular magnetic field components, collisional age, temperature anisotropy or ion and electron beta. Our discussion encompasses the interplay of magnetic field and plasma fluctuations that characterize this dynamic environment and reveals that although ion beta controls a position of the spectral break between the inertial and kinetic ranges, other mentioned parameters determine the steepness of a transition range spectrum of both quantities. We are showing that these statistical results are in line with theoretical considerations.

## AS25-0367

# Turbulence, heating and sources of the slow Alfvenic solar wind

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Alfvenic fluctuations are found throughout observations of the solar wind. The fast solar wind is highly Alfvenic while the slow solar wind shows varying degrees of Alfvenicity, typically lower than in the fast wind. The normalized cross helicity, a proxy for Alfvenicity, decreases as a function of radial distance likely due to a combination of factors: a decrease in alignment of the velocity and magnetic fields due to fluctuations and the increased presence of inward propagating modes. Some of the slow wind has been shown to be highly Alfvenic, and often shows compositional characteristics similar to those of the fast wind. We discuss the dependence of the cross helicity on the choice of characterization scheme and as a function of radial distance and Mach number, noting that the Alfvenic slow wind shows lower cross helicity than the fast wind, unless solar wind acceleration is accounted for. We look at heating rates, entropy, and magnetic expansion at the source associated with Alfvenic slow wind streams in comparison with classically fast wind and discuss potential source regions. We hope to motivate discussion on the use of turbulence parameters as an important piece in characterizing the solar wind and studying its source.

## AS25-0482

# Statistical analysis of magnetic field spectra at interplanetary shocks: Solar Orbiter, Parker Solar Probe, and Wind

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We investigate the role of interplanetary (IP) shocks in solar wind turbulence as thin boundaries using observations from Solar Orbiter, Parker Solar Probe, and Wind. We adopt fast forward (FF) and reverse (FR) quasi-perpendicular shock sets for the statistical approach. Our previous study suggested that the spectral properties of magnetic fields remain largely conserved across various types of IP shocks, except for FR shocks—likely due to interactions with high-speed streams. To further explore the transient region near IP shocks in terms of magnetic field turbulence dissipation, we estimate the characteristic timescale for variations in the transition range spectral index using 1-min computation intervals sliding every 10 s. Additionally, we analyze key parameters influencing spectral index formation, namely cross-helicity and fluctuation amplitude. Our findings reveal that spectral index exhibits an immediate transition from upstream to downstream across all shock sets, without a gradual or asymptotic evolution over extended timescales (e.g., 10 minutes). Moreover, cross-helicity appears to be the dominant factor governing spectral index steepness, rather than fluctuation amplitude. A statistical analysis indicates that IP shocks systematically reduce cross-helicity leading to a shallower spectral index in the downstream region. This suggests that the observed spectral index modification results primarily from cross-helicity reduction rather than the direct impact of the shock itself. Finally, we examine the relationship between spectral index and solar wind speed within stream interaction regions and rarefaction regions to further support the hypothesis that IP shocks act as thin boundaries in magnetic field energy dissipation, delineating distinct plasma environments.

## AS25-0624

# What heats the solar wind? Lessons from PSP and future perspectives

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Understanding the nature and importance of various proposed heating processes that result from turbulent dissipation is imperative in describing a range of collisionless systems. We highlight the importance of kinetic phase space signatures of heating as pivotal in providing necessary constraints on turbulent dissipation. Understanding mechanisms through diffusive approximation schemes is largely a tractable problem that can be studied with modern plasma instrumentation. We highlight recent progress in understanding signatures of kinetic dissipation and particle heating using the Parker Solar Probe (PSP) mission. Importantly, our observations reveal that a range of heating mechanisms (stochastic heating, cyclotron resonance, and Landau damping) that couple turbulence to plasma heating, which contribute to dissipation in both electrons and proton. Our results highlight the importance in observing accurate phase-space signatures in constraining the strength and importance of these mechanisms. The use of non-parametric approximations to particle distribution functions (via Hermite polynomials, Radial Basis Functions, Machine Learning Methods) is pivotal in understanding and characterizing these heating mechanisms. While our observations are from PSP, we discuss future implementation of these techniques on current and future plasma missions (MMS and Plasma Observatory).

## AS25-0718

# Multispacecraft analysis of MHD turbulence in interplanetary shocks

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Turbulent processes play a fundamental role in the dynamics of solar wind plasma fluctuations, driving energy transfer within the heliosphere and contributing to particle acceleration. We investigate the nature of large- and small-scale fluctuations in the upstream and downstream regions of interplanetary shocks. By analyzing magnetic field fluctuations with both conventional and advanced methods, we investigate variations in correlation length, Taylor scale, and Reynolds number across these regions. We derive correlation lengths through autocorrelation and cross-correlation functions across the three spacecraft. Our analysis uses plasma and magnetic field data from the ACE, WIND, and DSCOVR missions. A decrease in Reynolds number from upstream to downstream suggests a resetting of turbulence in the studied cases. These findings provide insights into the structural evolution of turbulence across shocks. Building on case study results, we extend our analysis with a statistical investigation of these parameters across multiple shock events. Additionally, we perform a statistical analysis of WIND satellite data from 2005 to 2023 and shoow the dependence of correlation length on different intervals chosen for computing the autocorrelation function.

## AS25-0730

# Evidence for link between turbulence and generation of ion cyclotron waves via the helicity barrier effect in the solar wind

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The dissipation and heating of collisionless plasma in the inner heliosphere is a significant unresolved problem in space physics. The helicity barrier theory suggests a possible mechanism for these processes, but it requires validation through analysis of spacecraft data. We assess the validity of the parameter regime associated with the helicity barrier in the solar wind over a range of heliocentric distances using Parker Solar Probe and Solar Orbiter. We use the Politano-Pouquet law to estimate the energy and cross helicity cascade rates in the solar wind and compare the values to radial distance, the polarisation and prevalence of ion cyclotron waves. We find that the amplitude and prevalence of left-hand-polarised waves in the solar wind is directly correlated with the total energy and the cross helicity cascade rate of the turbulence. Our measurements are consistent with the helicity barrier being active in all solar wind intervals that we study and we demonstrate the uncertainty in calculating energy and the cross helicity cascade rates in this study.

## AS25-0789

# Testing closure learned from fully kinetic simulations of magnetosheath turbulence

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Understanding the interactions between the solar wind and the magnetosphere requires multi-scale modelling to resolve magnetohydrodynamic, ion and electron kinetic scales, owing to the collisionless character of plasma turbulence. This leads to computational complexity that reduced models aim to address.

In this study, we investigate decaying turbulence in the magnetosheath by performing comparisons between the ECsim (a fully-kinetic Energy Conserving PIC) model and a computationally lighter model Menura (a hybrid PIC). Menura resolves kinetic ion scales but the influence of massless electrons is provided only via the pressure closure.

We present a detailed analysis of the pressure-strain interaction terms, electromagnetic work and cross-scales fluxes demonstrating relatively good agreement between the two models. Our findings confirm several established results from fully kinetic Vlasov and PIC simulations, such as connections between coherent structures and energy conversion, including more recent magnetosheath observations. Furthermore, we are extending these insights to a novel magnetosheath regime for a hybrid PIC model, which has generally received less attention in such studies. However, discrepancies were also identified, such as Zenitani measure (electromagnetic work done by the non-ideal electric field) and absolute values of energy dissipation which are model-dependent.

In the effort to further improve electron pressure closure, we train a neural network surrogate on ECsim generated data (high fidelity model). We show that closure performs reasonably well out-of-sample on different ECsim runs and provides consistent scaling for predicted pressure-strain in these new runs as a function of traceless stress, vorticity and the mean square total current density.

## AS25-0807

# Impact of Imbalance on Solar Wind Turbulence Across Inertial and Sub-Ion Scales

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Recent theoretical advancements suggest that the statistical properties of sub-ion scale turbulence are strongly influenced by the degree of imbalance in counter-propagating wave packet fluxes at MHD scales due to the "helicity barrier" (HB) effect. In this talk, we use data from Parker Solar Probe, Solar Orbiter, and WIND to test HB model predictions and examine how 3D anisotropy, higher-order statistics, and kinetic Alfvén wave helicity vary between balanced and imbalanced solar wind intervals. We further estimate proton and electron heating rates to assess how imbalance and plasma β, the ratio of magnetic to thermal pressure, govern the partitioning of dissipated magnetic energy between ions and electrons. Our findings provide observational constraints on turbulence-driven heating and offer new insights into the mechanisms shaping the turbulent cascade in the solar wind.

## AS25-0896

# Phase-space turbulent cascades in space plasmas

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Understanding energy conversion and dissipation processes leading to plasma heating and particle energization in nearly-reversible space and astrophysical plasmas requires investigating kinetic-scale dynamics, which, as a result of the weak collisionality, occur in the entire six-dimensional phase space. Indeed, various non-equilibrium velocity-space structures in the plasma distribution function are often observed in heliospheric plasmas.

Employing the Hermite decomposition of the plasma velocity distribution function, the generation of these structures can be interpreted as a turbulent cascade occurring in the entire phase space. Such a cascade transfers the distribution function's fluctuations with respect to the local Maxwellian equilibrium from large to small scales in velocity space. In this talk, I will review some recent results on this topic based on both numerical simulations and in-situ observations.

## AS25-0979

# Assessing the Irreversible Nature and the Energy Transfer of Magnetic Fluctuations at Sub-Ion Scale Plasma Turbulence

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An intriguing aspect of space plasma turbulence is the emergence of an additional power-law spectral domain, characterized by a spectral exponent near -8/3, occurring at scales around and below the ion-inertial length. This spectral feature has been linked to a distinct turbulent regime driven by alternative wave modes and a unique energy cascade mechanism. However, both this interpretation and the irreversible nature of energy fluctuations at these scales remain subjects of debate. In this work, we examine the irreversibility and the occurrence of an energy cascade of magnetic field fluctuations at ion and sub-ion scales using high-resolution magnetic field data from the space missions, as Cluster and PSP. Furthermore, we compare our results with theoretical predictions from Hall-MHD shell model turbulence.

## AS25-1121

# Dependence of extreme minor-ion heating on β and imbalance in solar-wind turbulence

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Minor ions in the solar corona are heated to extreme temperatures, relative to the bulk electrons and protons comprising the plasma. Their highly nonthermal distributions make minor ions sensitive probes of the collisionless processes that power the corona and the solar wind. Among these processes, two main mechanisms of dissipating Alfvénic turbulence that are capable of preferentially heating ions perpendicular to the magnetic field—ion-cyclotron-wave (ICW) heating and stochastic heating—depend on plasma β, the level of imbalance between outward- and inward-propagating Alfvénic fluctuations, and ion charge state and mass. We present results from six Pegasus++ hybrid-kinetic particle-in-cell simulations of both imbalanced and balanced turbulence at proton β=[1/16,0.3,1], each including multiple minor-ion species. Clear phase-space signatures of oblique ICW heating and stochastic heating manifest in ion velocity distribution functions and field-particle correlations. ICW heating is more extreme for heavier ions and is promoted in simulations of imbalanced turbulence where we see the natural formation of a helicity barrier and its associated signatures: A steep transition-range electromagnetic spectrum, proton-cyclotron waves propagating in the direction of imbalance, significantly enhanced proton-to-electron heating ratios, and ion temperatures that are considerably more perpendicular with respect to magnetic field. We find scalings for ion temperatures with species' charge and mass, and how they are influenced by the degree of imbalance and proton β. By comparing with measurements taken by Parker Solar Probe and Solar Orbiter, these physically informed scalings and corresponding signatures could be used to distinguish turbulent heating regimes within the solar wind.

## AS25-1212

# The interaction of plasma turbulence and collisionless shock waves in 2.5D hybrid simulations

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Collisionless shock waves and plasma turbulence play fundamental roles in particle acceleration and energy dissipation in space plasmas. Electromagnetic fluctuations in the vicinity of a shock facilitate efficient particle acceleration. In addition to the fluctuations generated self-consistently by the particles interacting with the shock, the upstream solar wind is itself inherently turbulent. We study the influence of this pre-existing plasma turbulence on shock front dynamics and investigate how turbulence evolves in the downstream region of a shock. We employ a novel modelling setup in which we use MHD simulations to generate turbulent fields that are dynamically input to our 2.5D hybrid shock simulations. We present simulation results for shock waves with varying magnetic obliquities, Alfvén Mach numbers, plasma beta conditions, and turbulence amplitudes. Our results of the downstream turbulence spectra can be compared with spacecraft observations of interplanetary shock waves. Preliminary simulation results on how particles move and gain energy in these turbulent fields are also presented.

## AS25-1256

# Study of turbulence and kinetic effects in the inner heliosphere by means of Solar Orbiter observations

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Turbulence in plasmas involves a complex cross-scale coupling of fields and distortions of particle velocity distributions, with the generation of non-thermal features. Here, by means of new measurements by Solar Orbiter, the radial nature of the turbulent magnetic fluctuations around ion scales during the expansion of the wind, has been investigated. The ion scales appear to be characterized by the presence of non-compressive coherent structures, such as current sheets, vortex-like structures, and wave packets identified as ion cyclotron modes, responsible for solar wind intermittency and strongly related to the energy dissipation. Particle energization, temperature anisotropy, and strong deviation from Maxwellian, have been observed in and near coherent structures, both in in-situ data and numerical simulations. Furthermore, kinetic effects for both protons and alpha particles have been studied in presence of switchbacks, large deflections of the magnetic field which occur simultaneously with a sudden increase in the radial solar wind velocity. Very interestingly we observe a clear correlation between switchbacks and alpha particle temperature, but not with proton temperature, suggesting a role of magnetic field deflections in preferentially heating heavy ions. Finally, we investigate both the contribution of the switchbacks to the turbulent cascade and the presence of waves close to isolated switchbacks and their role in the generation of these deflections.

## AS25-1273

# Solar Energetic Particle propagation in the turbulent interplanetary magnetic field

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Ions and electrons accelerated during solar flare and Coronal Mass Ejection events propagate away from the Sun through the interplanetary magnetic field (IMF), giving rise to the heliospheric Solar Energetic Particle (SEP) population. Despite decades of measurements by spacecraft, many questions remain on the way in which SEP acceleration and propagation processes shape their spatial and temporal distribution in the heliosphere. In particular the way in which IMF turbulence influences propagation parallel and perpendicular to the average magnetic field is the subject of much recent research. This talk will review classical approaches to the description of turbulence effects as well as more recent work, including studies of non-diffusive SEP propagation and the consequences of magnetic field line meandering. It will present a recent model of IMF turbulence in Parker spiral geometry which has been used as input to test particle simulations of SEPs. It will introduce SEP guiding centre drifts associated with the large scale IMF structure and discuss how they are modified by the presence of a turbulent field.

## AS25-1289

# Reconnection-driven agyrotropic electron distributions in turbulent plasmas and the role of electron velocity shears

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Deformations of the particle distributions are both expected and observed in collisionless space plasmas. These are typically correlated with heating mechanisms and pressure anisotropy can be an important source of instabilities. The mechanisms allowing for the generation of non-thermal distributions and their direct connection with other fundamental plasma mechanisms such as turbulence and magnetic reconnection, however, still represent an open issue. We investigate their interplay by means of high-resolution 2D fully kinetic simulations of plasma turbulence. We observe intense electron-scale current sheets forming as the result of the interaction of ion-scale magnetic vortices and then undergoing standard or electron-only magnetic reconnection. We compute the agyrotropy of the ion and the electron pressure tensors and find the latter to peak in correspondence of X points and separatrices, which are also regions of intense electron velocity shears. We also compare the agyrotropy of the pressure tensors with the non-Maxwellian measure of the particle velocity distributions. Finally, we compute and discuss the agyrotropy and the non-Maxwellian measure in observations by Magnetospheric Multiscale. Our results agree with those from previous simulations of magnetic reconnection in a single current sheet and extend the analysis to multiple reconnection events that are spontaneously driven by sub-ion scale turbulence. They also agree with theoretical models of anisotropy generation driven by velocity shears.

## AS25-1295

# Study of unstable proton velocity distributions in the Solar Wind motivated by Parker Solar Probe observations near perihelia

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Recent measurements of solar wind ions by the SPAN-I instruments aboard the Parker Solar Probe (PSP) spacecraft at Encounter 17 and nearer reveal evidence of anisotropic unstable non-Maxwellian proton velocity distributions, including core, beam with hot 'hammerhead' populations where $T_\perp/T_\parallel \neq 1$. Beams with super-Alfvénic speeds with respect to the core were detected. These non-Maxwellian velocity distribution functions (VDFs) correlate with increased circularly polarized ion-scale kinetic wave activity, observed by the PSP/FIELDS instrument, indicative of development of ion-kinetic instabilities. Inspired by these PSP observations, we use nonlinear hybrid models to explore the development of the anisotropic hot-beam VDFs and to simulate the growth and nonlinear phase of the ion kinetic instabilities in various initial linearly unstable states. We find combined ion-cyclotron (IC) and magnetosonic (MS) instabilities, which produce the polarized ion-scale wave spectra. The non-equilibrium structures of the proton VDFs during the nonlinear phase of evolution are in qualitative agreement with PSP/SPAN-I data near perihelia. Based on our modeling results, we infer that the collisionless interactions between particles and ion-scale wave in the unstable state provide the route for energy transfer from large scale (fluid) to small scale magnetic fluctuations (waves) to random particle motion resulting in anisotropic heating of the solar wind plasma, thus addressing the long-standing question of solar wind extended heating in the inner heliosphere.

## AS25-1324

# Energy dissipation in turbulent space plasmas: a multi-scale analysis using numerical simulations and spacecraft observations

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Our efforts in understanding the dynamics of turbulent space plasmas rely on three complementary approaches: theoretical models, spacecraft measurements, and numerical simulations. In the last decades, these have been combined to investigate energy dissipation in collisionless plasmas, one of the fundamenal open problems in space and astrophysical environments to date. Numerical simulations represent "le trait d'union", as they are key to both validate theoretical models and provide a three-dimensional counterpart to observations. I will show and discuss how we can use advanced multi-scale analysis techniques on numerical simulation data to investigate key aspects of the turbulent plasma dynamics, e.g., the emergence of intermittent current structures and how these relate to energy transfer and dissipation. After focusing on the solar wind, I will then present preliminary results from new spacecraft observations hinting at the occurrence of plasma turbulence in the top-side Earth polar ionosphere, which is magnetically connected to the solar wind.

## AS25-1350

# Unveiling Plasma Energization and Energy Transport in the Earth's Magnetospheric System through Multi-Scale Observations: the Plasma Observatory M7 candidate mission

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Energetic plasma is everywhere in the Universe. The Earth's Magnetospheric System is a key example of a complex and highly dynamic cosmic plasma environment where massive energy transport and plasma energization occur and can be directly studied in situ. Despite the large number of available observations, however, we still do not fully understand how plasma energization and energy transport work. Observations and simulations suggest that the key physical processes driving plasma energization and energy transport occur where plasma on fluid scales couple to the smaller ion kinetic scales, at which the largest amount of electromagnetic energy is converted into energized particles. Plasma Observatory will be the first mission having the capability to resolve scale coupling in the Earth's Magnetospheric System through measurements at seven points in space, covering simultaneously ion and fluid scales in the foreshock, bow shock, magnetosheath, magnetopause, magnetotail current sheet, and transition region. By resolving scale coupling in fundamental plasma processes such as shocks, reconnection, turbulence, plasma instabilities, plasma jets, field-aligned currents and their combination, these measurements will allow us to answer the two Plasma Observatory science questions (Q1) How are particles energized in space plasmas ? and (Q2) Which processes dominate energy transport and drive coupling between the different regions of the Earth's Magnetospheric System? Going beyond the limitations of Cluster and MMS four-point constellations, which can only resolve individual scales, Plasma Observatory will transform our understanding of the plasma environment of our planet with a major impact on the understanding of astrophysical plasmas too.

## AS25-1368

# Multiscale gradient estimation and the dynamics of plasma structures: the Plasma Observatory perspective

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Multispacecraft constellations such as Cluster, THEMIS, and MMS significantly advanced our understanding of plasma dynamics in different regions of space, resolving one spatial scale at a time, and overcoming limitations due to single-point measurements. They highlighted that plasma processes span multiple scales, from large fluid dynamics to smaller kinetic phenomena, posing the basis for the critical importance of investigating cross-scale coupling of plasma processes (magnetic reconnection, jets, shock waves, and turbulence). The next logical step for improving single-scale missions, is to perform multiscale measurements at the same time. A new era of spacecraft constellations, such as the future NASA mission HelioSwarm in the solar wind, and the ESA Phase A Plasma Observatory in the near-Earth plasma, is fully devoted to this purpose.

In this work, we analyze numerical simulations of space plasma turbulence though a virtual multi-scale spacecraft constellation, thus modeling the Plasma Observatory measurements of velocity and magnetic field spatial gradients at different scales. Resorting to the magnetohydrodynamic (MHD) theory of gradient tensor geometrical invariants [1, 2], we attempt to establish a link between MHD and kinetic-scale dynamics. To this purpose, the gradient tensor invariants are examined and the correlation between different plasma structures and the respective kinetic features are investigated. This study is essential for advancing the understanding of the role of structures and energy transfer in collisionless plasmas, thereby supporting future multiscale missions such as HelioSwarm and Plasma Observatory.

1) Consolini, G., et al., ApJ, 812(1), 84.
2) Quattrociocchi, V., et al, ApJ, 878(2), 124.

## AS25-1409

# Radial evolution of an Alfvénic slow wind stream followed by an interplanetary shock: observations by Solar Orbiter and Wind

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Solar Orbiter offers a unique opportunity to study the interrelation between the Sun and the heliosphere and the fundamental processes leading to the origin and acceleration of the solar wind. Along its orbit, it crosses the Sun-Earth line so that the observed solar wind can be investigated also at L1, giving an opportunity to study its radial evolution.

One of the main features of the ambient solar wind is the presence of Alfvénic fluctuations, thought to play a fundamental role in different heliospheric processes, such as solar wind heating and acceleration, energetic particle acceleration, and cosmic ray propagation. Moreover, they may also drive the geomagnetic activity although large-scale interplanetary structures, such as interplanetary coronal mass ejections (ICMEs), are the dominant phenomena causing intense geomagnetic storms.

Within this context, this study focuses on the investigation of an Alfvénic slow wind stream followed by an ICME with a strong interplanetary shock ahead. The combined observations by Solar Orbiter and Wind at L1 allow to study the radial evolution of turbulence in the Alfvénic slow stream in order to understand better how Alfvénicity evolves and what are the mechanisms responsible for its evolution. We further exploit this dataset by addressing the largely debated problem of the shock-turbulence interplay, where we compare the properties up upstream/downstream fluctuations for this event both at Solar Orbiter and Wind. Finally, we tie the behaviour of upstream/downstream fluctuations to the observed energetic particles, being efficiently accelerated to energies of up to 1 MeV at Solar Orbiter and Wind.

## A29 Advances in understanding solar transients and particle events in the corona and heliosphere

### AS25-0029

# The widespread solar energetic particle event on 2022 January 20: The role of the magnetic cloud

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On 2022 January 20, the Energetic Particle Detector (EPD) on board Solar Orbiter measured a solar energetic particle (SEP) event showing unusual first arriving particles from the anti-Sun direction. Near-Earth spacecraft separated 17° in longitude to the west from Solar Orbiter measured classic antisunward-directed fluxes. STEREO-A and MAVEN separated 18° to the east and 143° to the west from Solar Orbiter respectively, also observed the event, suggesting that particles spread over at least 160° in the heliosphere.

The aim of this study is to investigate how SEPs accelerated and transported to Solar Orbiter and near-Earth spacecraft, as well as to examine the influence of a magnetic cloud (MC) present in the heliosphere at the time of the SEP event onset on the propagation of the energetic particles.

The SEP event is related to a M5.5 flare and a fast CME-driven shock of ~1433 km/s which injected particles within and outside an MC. The timing and anisotropies of the particles arriving to Solar Orbiter along with the radio and X-ray data strongly suggest that the particles were injected by the coronal shock along the longest (western) leg of an interplanetary CME still connected to the Sun at the time of the release of the particles.

## AS25-0221

# Unexpected solar energetic particle events observed by Solar Orbiter: insights into shock acceleration and particle transport

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Gradual solar energetic particle (SEP) events, typically generated by coronal mass ejection (CME)-driven shocks, arise from a complex interplay between acceleration processes at the shock and dynamic transport along the interplanetary magnetic field. Our understanding of these events has been largely limited by the sparse coverage of spacecraft in the inner heliosphere and the capabilities of previous particle detectors. The Solar Orbiter (SolO) ESA mission, via its Energetic Particle Detector (EPD) suite has now provided unprecedented high-resolution measurements that reveal unexpected SEP phenomena during solar cycle 25. We present a detailed analysis of these observations, which include unique behaviors such as distinct particle escape patterns from shocks, delayed arrivals of high-energy particles, and bidirectional injection events. By integrating both in-situ measurements and simulation results, we explore the potential mechanisms driving these anomalies and demonstrate that the inner heliospheric environment is far more complex than suggested by the classical SEP framework.

## AS25-0226

# Longitudinal Extent of 3He-rich Solar Energetic Particle Events near 1 au

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Multi-spacecraft observations of 3He-rich solar energetic particle (SEP) events are scarce but much needed in order to understand and properly constrain the source and transport of these remarkably enriched 3He SEP events. In this paper, we report 15 3He-rich SEP events that were detected by ACE, STEREO, and Solar Orbiter near 1 au during Solar Orbiter's aphelion pass at the end of 2022 and early 2023. Three (five) of these events were detected simultaneously by at least two (three) spacecraft at up to ~40° longitudinal separation, while seven events were detected by only a single spacecraft even though an adjacent spacecraft was less than 20° apart. Using a magnetic connectivity tool, we show statistically that there is a >50% probability of detection when the spacecraft modeled footpoints have an angular separation angle of <24° to the potential source region back at the Sun. This supports previous studies that the source of these 3He-rich SEP events is narrow in longitudinal extent. On the other hand, the magnetic connectivity due to the presence of CMEs, footpoint motion, and/or field line meandering may also lead to difference in a detection at 1 au.

## AS25-0301

# Solar Energetic Electron Events Observed by Solar Orbiter and Wind on 2022 March 6

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Solar energetic electron (SEE) events are one of the most common solar particle acceleration phenomena detected in the interplanetary space. Here we present a comprehensive study of three SEE events observed by SolO/EPD at 0.5 AU and one SEE event by Wind/3DP at 1 AU on March 6, 2022 when the two spacecraft were separated by 1º in longitude. According to the velocity dispersion analysis, the solar release start-time (peak-time) of SolO event #1 (#3) agrees with the solar release start-time (peak-time) of the Wind event within uncertainties. Moreover, the three SolO SEE events exhibit, respectively, a single-power-law (SPL) energy spectrum a double-power-law (DPL) spectrum that bends downward at 22.7±10.3 keV, and a DPL spectrum that bends downward at 9.3±3.4 keV. The Wind/3DP SEE event shows an SPL energy spectrum. During the event peak, the electron pitch angle width at half maximum is about 13º-20º at 7.4 keV for the three SolO events, while it is about 47º at 4.2 keV for the Wind event. On the other hand, SolO event #1 and #3 are accompanied by two HXR microflares, while event #3 is also associated with multiple EUV jects. All these microflares/jets, as well as the magnetic field lines that connect to SolO and Wind, originate from the same active region (AR12957). These results suggest that the three events detected by SolO likely arise from different sources/processes at the Sun, and then they merge to one event during the propagation from 0.5 AU to 1 AU.

## AS25-0395

# A tale of two shocks

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It was the best of times, it was the worst of times – for two traveling interplanetary shocks observed by Solar Orbiter on November 29 and 30 in 2023. We investigate these two very dissimilar shocks which were observed within less than 27 hours to elucidate obviously present non-equilibrium features. We find very different behavior of particles at the two shocks which are – of course – due to differences in the two shocks.

The first of the two shocks was observed at 07:51:17 on Nov. 29, 2023, was quasi-parallel and the weaker of the two shocks. It had no or only a minimal effect on the suprathermal particle population which was anisotropic and streaming away from the Sun. It was likely running into a small ICME and exhibited upstream wave activity with a dominant period just below one second.

The following shock on Nov 30, 2023 (10:47:26) was stronger and quasi-perpendicular. Wave activity upstream of this shock was weaker than at the first and limited to the shock ramp, as expected for a quasi-perpendicular shock. Upstream protons and He2+ particles show clear core-beam velocity distribution functions. Suprathermal ions upstream of the second shock are more isotropic than around the first shock but nevertheless show a clear bump-on-tail distribution which lasts for approximately two gyroperiods. The region downstream of this shock is rich in further unusual properties of the suprathermal ions. These exhibit strong non-equilibrium and anisotropic features in their differential intensities.

## AS25-0400

# Influence of the dynamic solar wind on CME propagation from a multi-spacecraft perspective

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Coronal mass ejections (CMEs) are the main drivers of interplanetary shocks and space weather disturbances. Strong, Earth-directed CMEs with a southwards magnetic field configuration can severely impact space and ground systems, and their timely prediction can enable us to mitigate their negative effects.

The novel heliospheric wind and CME propagation model Icarus 3.0 (Baratashvili et al. 2025) was recently upgraded to the latest MPI-AMRVAC 3.0 version (Keppens et al., 2024). This upgrade includes a dynamic driving of the inner boundary conditions (BCs) which enables inner BCs to be updated every two hours after the simulation starts. This way, the solar wind is no longer stationary in the co-rotating framework as new information propagates continuously from the inner boundary.

Icarus is well-suited for multi-spacecraft studies. In this study, we select a CME observed by multiple spacecraft during September 2021 which we use to evaluate the performance of the model. We identify the CME source region, reconstruct its characteristic parameters and initiate the CME propagation in Icarus 3.0 with a cone and a spheromak CME model. The propagation of the CME is investigated in the steady and dynamic solar wind configurations, and the modelled conditions are then compared to in-situ measurements.

We find that the dynamic solar wind solution more accurately represents the observed solar wind than the previously stationary wind model. As the solar wind background significantly affects the propagation of CMEs, such improvements allow us to better reproduce their observed signatures in situ, advancing our space weather forecasting abilities.

## AS25-0552

# Investigating Coronal Structures Using WISPR Observations from Parker Solar Probe

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The Parker Solar Probe (PSP), launched in 2018, has collected a substantial dataset with the Wide-Field Imager for Solar Probe (WISPR), providing new opportunities to study coronal structures in visible light. These include streamers, dynamic outflows of blobs, and expanding coronal mass ejections (CMEs). Features moving along the observer's line of sight appear brighter due to their proximity to the Thomson Sphere (TS), whose geometry varies with the spacecraft's distance from the Sun. Comparing theoretical brightness predictions with observations can reveal missing physical processes and enable the development of new methods to extract physical properties from brightness variations. We present several examples, including stationary coronal streamer structures and evolving CMEs, demonstrating how brightness fluctuations help infer the dynamics, scattering angles, velocities, spatial extents, and electron densities of these structures. To validate our findings, we employ multiple approaches, including magnetohydrodynamic (MHD) modeling and triangulation techniques, to determine the locations and dynamics of coronal structures.

## AS25-0572

# Suprathermal electron flows associated with magnetic clouds in the heliosphere—Helios 1/2 data revisited and Parker Solar Probe observations

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In this study we reinvestigate the Helios 1 and 2 plasma and magnetic field data for magnetic clouds observed in the inner heliosphere, at distances between 0.3 and 1 au, in order, to study the flow properties of suprathermal electrons in the energy range 50 to 430 eV. Taking into account the electron analyzer's spatial viewing direction, we find counter-streaming electron flows associated with all studied events. Usually the magnetic clouds were associated with a preceding fast-forward interplanetary shock which leads to an isotropic behavior of the electron Strahl, followed by a phase of turbulent variations in the flow directions in the sheath region behind the shock, an enhanced uni-directional flow of electrons associated with compressed ambient solar wind magnetic field ahead of the nose of the ICME, a counter-streaming flow inside the ICME cloud and a re-appearance of the electron Strahl behind it. The suprathermal electron flows on occasion also indicate the presence of compound streams made up of multiple ICMEs. This presentation presents a summary of our findings and comparisons with previous studies and the new observations from Parker Solar Probe.

## AS25-0994

# Surface Flux Transport of Photospheric Fields: Line-of-Sight versus Vector Assimilation

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The solar magnetic field plays a key role in solar and heliospheric physics. The field is most easily measured in the photosphere, from ground or space-based telescopes, and these measurements are the essential input for models of the solar corona and solar wind, in the form of full-Sun magnetic maps. As nearly all of these observations are along the Sun-Earth line, a full solar rotation (27 days) is required to completely view the solar surface. Standard observatory maps are constructed over the course of a rotation, so they contain data that is as much as 27 days old. Surface Flux Transport (SFT) models can mitigate this issue, by modeling the evolution of magnetic flux in regions not directly observed. The Open-source Flux Transport (OFT) model suite is an open-source package for creating full-Sun photospheric magnetic field maps via surface flux transport (SFT) modeling, now available on GitHub. The choice of the magnetogram source data for assimilation into an SFT is key discriminator of the resulting maps, as magnetograms from different instruments may be qualitatively similar but have important quantitative differences. Thus far, most SFT models assimilate line-of-sight (LOS) magnetograms, and there has been relatively little exploration of assimilation of vector magnetograms into SFTs. In this presentation, we show comparisons between assimilative SFT maps incorporating HMI vector magnetograms vs LOS magnetograms, as well as how other assimilation choices affect the resulting map properties. The implications for coronal and heliospheric models employing SFT maps will be discussed.

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## AS25-1060

# Modeling Heliospheric Flux-Ropes

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Magnetic flux ropes manifest as twisted bundles of magnetic field lines. They carry significant amounts of solar mass, flux and helicity in the heliosphere. The three-dimensional characterization of magnetic flux-ropes observed in the heliosphere has been a challenging task for decades. This is mainly due to the limitation to infer the 3D global topology and the physical properties from the 1D time series from any spacecraft. As the constellation of spacecraft in the heliosphere increases, the understanding of these structures departs from the traditional and simplistic visualization of a circular-cylindrical structure with a well-organized internal structure. To advance our understanding of magnetic flux-ropes whose configuration departs from the typical stiff geometries and conventional internal structures, here I present the evolution of analytical models with different physicsolution for a 3D flux-rope model with an arbitrary cross-section, global shape and complex internal structure.

## AS25-1140

# Multi-spacecraft observations of Fe-rich solar energetic particle events

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Among the characteristics of solar energetic particle (SEP) events that can vary dramatically from event to event is the heavy ion composition. This can be influenced by a number of factors, including the acceleration mechanism, transport effects, and properties of the particle seed population. Typically, high Fe/O abundance ratios are observed in smaller SEP events where the dominant acceleration mechanism is flare-associated reconnection. Occasionally, large SEP events generated by shocks driven by coronal mass ejections (CMEs) also exhibit high Fe/O ratios. Whether these enhancements are a result of the acceleration conditions (e.g., properties of the shock and/or seed population) or a direct contribution of flare-associated SEPs is still debated. Multi-spacecraft observations of such events are a useful contribution to this debate, as typically the spacecraft differ in their magnetic connection to the solar source region and the CME-driven shock. Here we present results from several multi-spacecraft, Fe-rich SEP events and discuss their compositional variations and what they may indicate for the source of the Fe enhancements.

## AS25-1253

# SPEARHEAD: First Results for High Energy Particle Research

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SPEARHEAD (SPEcification, Analysis & Re-calibration of High Energy pArticle Data) [https://spearhead-he.eu] is a Horizon Europe project dedicated to uncovering the mechanisms behind high-energy particle acceleration and transport during solar eruptions. By leveraging unprecedented datasets from leading heliophysics missions and ground-based observations, the project tackles three central science questions: how protons are accelerated beyond 100 MeV and electrons beyond 1 MeV, the release times and spectral characteristics of near-relativistic particles, and how coronal and interplanetary structures affect particle transport. Early results show significant progress in generating novel datasets, cross-calibrating instruments, and integrating observations with plasma models to produce event catalogues and open-access tools — laying the groundwork for revised datasets, improved methodologies, and valuable resources for the scientific community. This presentation shows insights into the recent Ground Level Enhancement (GLE) 74 on 11 May 2024, along with the implementation and statistical analysis of proton (E>100 MeV) and relativistic electron catalogues from Solar Orbiter, Ulysses, and the Solar and Heliospheric Observatory, offering a deeper understanding of high-energy particles.

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## AS25-1275

# Particle acceleration and transport during the Sub-GLE event on 8 June 2024

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On June 8, 2024, an M9.8 solar flare erupted from Active Region 13697 at S17W72, near the west limb of the Sun. The flare was associated with a coronal mass ejection (CME) propagating in a direction that was favorable for magnetic connection with Earth, allowing for an exceptional opportunity to investigate particle acceleration and transport mechanisms in the inner heliosphere. An analysis of EUV observations from the Solar Dynamics Observatory (SDO) reveals that smaller transient structures that formed before the main CME become entrained within the CME sheath. In addition, high-quality images from SOHO and STEREO-A coronographs showed a broad CME-driven shock, enabling us to run shock modeling techniques and a detailed analysis of shock properties connected to different spacecraft.

Strong Solar Energetic Particle (SEP) events were recorded at Earth by GOES and SOHO/ERNE as significant enhancement of particle fluxes occurred in the >100 MeV and >500 MeV channels. STEREO-A also recorded increased fluxes of protons, electrons, and heavy ions (He, C, O, and Fe) at this time. The quiet long-lasting background period before this event allows for modeling both the acceleration and transport of energetic particles. Further to that, the event was classified as a sub-GLE. We present a detailed study of the relation between the energetic particles measured in situ at different points in the heliosphere with the CME-shock modeling. A particle transport model is employed to investigate the conditions of high-energy protons and electron propagation, constraining their acceleration and escape times in relation to the shock dynamics.

## AS25-1392

# Multi-Spacecraft Measurements of Coronal Mass Ejections and Energetic Storm Particle Events Between L1 and STEREO-A: Solar Cycle 25

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The return of STEREO-A to the proximity of the Sun-Earth line in 2022–2024 combined with the enhanced solar activity has resulted in numerous coronal mass ejections (CMEs) and energetic storm particle (ESP) events being measured simultaneously at nearly the same heliocentric distance by two spacecraft (STEREO-A and ACE, Wind or DSCOVR at L1) with some events also measured by Solar Orbiter. A dedicated analysis of all in situ CME measurements from 2022 to 2024 has revealed that the angular (full-)width of magnetic ejecta (MEs) within CMEs is of the order of 35–40° and that some large-scale properties can vary for separations of 5–10°. The properties of the CME sheaths are found to vary on smaller scales, confirming past studies; however detailed analyses of specific well-observed case studies reveal that the ME and sheath shapes may not always conform to our current paradigm. In addition, the significant solar activity in solar cycle 25 has resulted in numerous ESP events being measured jointly by ACE and STEREO-A, revealing how the fluxes and type of ESP vary with longitudinal separations.

## AS25-1421

# Modeling and Multi-Spacecraft Observations of the October 2021 SEP Event: Towards Predictive Capabilities

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We present a comparison of numerical modeling and multi-spacecraft observations of the October 2021 SEP event (cf. Palmerio et al. 2024), aiming to develop physics-based predictive simulation model of SEP profile and improve its prediction performance. Observations from PSP, SolO, BepiColombo, SOHO, and STEREO-A are compared with simulations. We reconstruct CME propagation using the SUSANOO model (Shiota et al.2014, 2016), driven by interplanetary scintillation data (Iwai et al. 2019), to derive CME shock parameters. These parameters are then used in a focused transport equation-based model to determine the SEP energy spectrum. This model relies on the mean free path, acceleration rate, and injection efficiency. We will discuss comparison with observed SEP fluxes and simulated fluxes at multiple locations. Furthermore, we will present about developing methods to predict the optimal ranges of these key model parameters, ultimately contributing to enhanced forecasting capabilities of SEP profile.

## AS25-1476

# Energetic particle signatures of interplanetary shock waves detected with Solar Orbiter

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High-energy charged particles of solar origin are effectively accelerated and disseminated at the same time at the fronts, within sheaths, and foreshock stages of shock waves driven by the Coronal Mass Ejections (CMEs). In this study, we investigate four fast forward (FF) shock waves that affected accelerated energetic particles in interplanetary space between January and May 2023. The four IP shocks were identified based on data from the SWA-PAS Proton Alpha Sensor of the Solar Wind Analyzer and the MAG Magnetometer. We consider events of synchronised omnidirectional acceleration of low-energy ions; dissemination of electron and ion fluxes on a strong magnetic cloud at a close distance from the Sun; asynchronous approach of light and heavy ions accelerated on a shock wave after a strong backside solar flare on 2023/05/16. We study some of the features mentioned above using data from the EPD Energetic Particle Detector suite.

We demonstrate that various phenomena in the heliospheric plasma and interplanetary magnetic field strongly affect the propagation, acceleration, transport, and spectral evolution of suprathermal and high-energy charged light and heavy ions, as well as electrons.

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## A30 Comparative Magnetospheres and Associated Regions

### AS25-0148

# Magnetosheath jets at Mars and Earth: Similarities and differences

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Magnetosheath jets are transient plasma structures with enhanced dynamic pressure, commonly observed downstream of the quasi-parallel bow shock. These jets are believed to form at the bow shock and propagate through the magnetosheath, potentially impacting and deforming the magnetopause. While magnetosheath jets have been studied at Earth for nearly 30 years, observations in other planetary environments, such as those of Mars and Jupiter, are relatively recent. To compare jet properties across different planetary environments, statistical studies are essential. Although such studies exist for Earth's plasma environment, they have been lacking for other planets. The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, with its full suite of plasma instruments, has been collecting data in the Martian plasma environment for over 10 years. Using this extensive dataset, we present the first statistical study of magnetosheath jets at Mars. Our analysis reveals that Martian jets are mostly density-driven, exhibit an increased magnetic field, and have a decreased temperature compared to the surrounding plasma. We conclude that Martian jets are generally similar to those at Earth, particularly those downstream of the quasi-parallel bow shock.

## AS25-0170

# Different Faces of the Martian Magnetosphere

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The Martian magnetosphere contains components of the induced and intrinsic magnetospheres. Since we can not get a global snapshot of the magnetosphere we use a statistical picture based on a large number of measurements. Depending on the choice of coordinate system and the data selection we can observe different faces of the Martian magnetosphere. If we map data in the Martian Solar Electric coordinate system, then we can separate the induced features of the magnetosphere which appears similar to the magnetosphere of Venus. If we use the Martian Solar Orbital coordinate system and select together the orbits with positive and negative By-component of the IMF, then the effects related to draped magnetic field and the high order harmonics of the crustal magnetic field are significantly weakened because of averaging over many orbits and a dipole-like magnetosphere of Mars becomes visible. If we select separately the orbits with positive and negative By-component we observe a twist of the magnetotail in the direction determined by the sign of By that is typical for a hybrid magnetosphere with the induced and intrinsic components. The intrinsic and induced components are also well separated when we select the orbits with northward IMF. Then we observe the features that are somewhat similar to those at the Earth magnetosphere. When we use the MSO coordinates and separate by the phase of Mars rotation, the tail topology occurs more complex. This indicates that the effects of the local crustal magnetic field turn out as being also important.

## AS25-0252

# Multi-Case Observations of 3-second Waves at Earth's Foreshock

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Ultra-low frequency (ULF) waves have been observed and studied extensively in the Earth's ion foreshock region, with their basic wave properties determined. One example of such ULF waves is the 3-second wave first observed in the ISEE magnetometer data [Le et al., 1992; Blanco-Cano et al., 1999] and more recently by MMS [e.g. Wang et al., 2021]. This class of ULF waves is always right-handed with periods near 3 seconds in the spacecraft frame, near circularly polarized and typically occurring in regions of high plasma β. They are often associated with suprathermal ion populations. In this study, we present magnetic field and plasma measurements of multiple case studies of 3-s waves as observed by MMS in the Earth's ion foreshock. We confirmed that these waves have a frequency of ~0.3 Hz (or 3.3s), and are circularly right-handed polarized in the s/c frame, consistent with earlier studies. We also utilized multi-spacecraft techniques when MMS is in a string-of-pearl formation to definitively determine the propagation direction of these waves to be anti-sunward in the plasma rest frame. We also observed diffuse ion population associated with the 3-s waves and, interestingly, strong modulation of the suprathermal ions by the 3-s waves. These 3-s wave intervals are typically observed to precede lower frequency 30-s fast magnetosonic waves after MMS observed a period of quiet solar wind and also be observed to be superposed on lower frequency waves or have higher 1-Hz waves superposed on them.

## AS25-0348

# Mercury's Magnetosphere under Extremely Low Alfvénic Mach Number Conditions: Comparative Insights from Earth and Ganymede

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We present an analysis of Mercury's magnetospheric response to extremely low upstream Alfvénic Mach number ($M_A$) conditions driven by ICME impacts detected by the MESSENGER spacecraft. Using data analysis techniques and three-dimensional MHD simulations, we demonstrate that these low $M_A$ conditions drastically alter Mercury's magnetosphere, transforming its typical, windsock shaped magnetotail to pairs of Alfvén wings that are highly inclined to the upstream flow direction. Additionally, during these low-$M_A$ ICME events, Mercury's dayside magnetosphere exhibits a weaker, more expanded bow shock and a significantly lower plasma density within the magnetosheath compared to its nominal state.

Recent studies have shown that rare, sub-Alfvénic upstream conditions also significantly affect Earth's magnetosphere interaction, generating Alfvén wings and providing an interesting comparison to those at Mercury. We further compare these phenomena with those of Jupiter's moon, Ganymede where the moon's intrinsic magnetic field interacts with the sub-Alfvénic flow of Jupiter's corotating plasma environment. These rare instances of sub-Alfvénic upstream conditions at Mercury offer brief windows of insight into the plasma environments of exoplanets, which often interact with a stellar wind that is nominally sub-Alfvénic due to their close proximity to their host star.

## AS25-0484

# Current systems at non-magnetized planets

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When the magnetized solar wind plasma encounters a non-magnetized planet, electrical currents will be induced in the ionosphere and in the deflected plasma, forming an induced magnetosphere.

As an example of a non-magnetized planet, we model the interaction between Mars and the solar wind using a hybrid plasma model (ions as particles, electrons as a fluid).

We investigate the morphology of the current systems at Mars, and how they depend on upstream solar wind conditions. Currents in the bow shock, in the magnetosheath, and in the ionosphere, are mapped. We also study the coupling and closure of the currents and draw conclusions for other non-magnetized planets.

## AS25-0608

# Magnetic field measurement by BepiColombo MIO MGF during cruising and prospects for the observations at Mercury

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By the BepiColombo mission we aim to understand the essential properties of the Herman intrinsic magnetic field and physical processes occurring in the Herman magnetosphere. We installed a dual magnetometer on the Mercury Magnetospheric Orbiter (MMO, MIO) with outboard (MGF-O) and inboard (MGF-I) magnetometers, which have been developed by European and Japanese groups, respectively. BepiColombo was launched in October 2018 and is now cruising in the interplanetary space. It will be inserted into the orbit around Mercury in November 2026 after flybys with the Earth, Venus, and Mercury. The MGF-O and MGF-I sensors are placed at the tip and in the middle of a 5m-long MAST deployed from the spacecraft. During the cruise phase, the MAST is stored in a container, and the two sensors are located close to the surface of the spacecraft. Although the magnetic noise radiated from the spacecraft is well restrained, considerable magnetic interference is measured by the sensors in the undeployed configuration. Moreover, since MIO, MPO (Mercury Planetary Orbiter) and a transfer module (MTM) are stacked during the cruise phase, MGF sensors suffer strong magnetic noise from MPO and MTM as well. The MGF team is taking high efforts to evaluate the magnetic field data at flybys and to remove the interference noise in order to identify natural phenomena in the space around planets. In this talk we give an overview of the operation and data from MIO MGF during the cruising period, and discuss the perspectives about the observation in the orbit around Mercury.

## AS25-0775

# Three second foreshock waves observed by the MMS mission

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Earth's foreshock is permeated by different backstreaming ion populations which are able to drive ion-ion instabilities leading to ultra-low frequency (ULF) waves. Among them are the 3 sec waves discovered by Le et al. (1992). These waves, as their name indicates, have 3 second periods and are observed in the plasma when the plasma beta is high. They are always right-hand nearly circularly polarized in the spacecraft frame and are convected downstream by the solar wind. Three second waves can exist in different regions of the foreshock where other waves can also exist. Blanco-Cano et al (1999) showed that when 3 second waves are in regions with a quiet magnetic field, they are accompanied by reflected ion beams. When the waves are observed in regions with a more irregular background field, the associated ions have more isotropic distributions. These authors also showed that sometimes 3 second waves are superposed to 30 second fluctuations. In this work we use Magnetospheric Multiscale (MMS) Mission magnetic field and plasma data to study in more detail 3 sec waves properties and their association with different ULF waves and ion populations. Dispersion solver analysis will also be performed to determine which instability drives the waves.

## AS25-0787

# Foreshock waves and ion scattering observed by the MMS mission

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The ion foreshock is the region upstream of Earth's quasi-parallel bow shock which is magnetically connected to the shock. Within it a variety of backstreaming ion populations exist, which are able to generate ion-ion instabilities leading to ultra-low frequency (ULF) waves. In this work we use Magnetospheric Multiscale (MMS) Mission magnetic field and plasma data to study a prolonged interval of steady interplanetary magnetic field (IMF) with above average solar wind helium abundance. When the IMF rotated to place the spacecraft in the ion foreshock region, MMS observed the entire process of the onset of a reflected ion beam, its pitch angle scattering, and the subsequent generation of ULF waves. The stable field conditions and MMS' unique capabilities allow us to study the properties of the generated 30 second sinusoidal waves from the moment they start to grow to the time when they reach large amplitudes and begin to steepen. We investigate how the ion beam is disrupted into a diffused distribution. We show that while backstreaming ions suffer pitch-angle scattering via wave particle interaction, the solar wind populations (protons and helium ions) remain relatively unchanged for some time. We also study possible changes in the wave properties due to the strong helium component.

## AS25-0857

# Comparison of electron acceleration at the Venusian, Martian, and terrestrial bow shocks

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The spatial size of collisionless shock waves is believed to play an important role in determining the maximum energy gain of particles accelerated at heliospheric and astrophysical shocks. In this study, we use data from the Parker Solar Probe, Solar Orbiter, Venus Express, MAVEN, and MMS to investigate and compare suprathermal (above 100 eV) electron acceleration at the Venusian, Martian, and terrestrial bow shocks. The identified shock crossings at Venus and Mars are compared to terrestrial bow shock crossings with similar Alfvénic Mach numbers (3–6). Preliminary results indicate that the spectral index for suprathermal electrons at Venus's and Earth's bow shocks exhibits a minimum for shock angles around 45 degrees and increases for shock angles closer to 0 and 90 degrees. The Martian bow shock crossings are also found to be similar to that of Earth except for two cases where a pronounced energetic seed population is present, resulting in an unusually hard spectral index at energies above 1 keV. Typically, the shock energizes particles with different energies differently. This raises the question of how important pre-existing energetic seed populations upstream of the shock (in the solar wind) are for shock acceleration efficiency. Ongoing work sets out to expand the seeded shock crossing database to examine the different bow shock's acceleration efficiency in the presence of pre-accelerated electrons.

## AS25-1143

# Dynamics in Mercury's magnetospheric cusps: Results from global coupled fluid-kinetic simulations

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MESSEGER observations at Mercury have revealed a remarkably dynamic magnetosphere, driven predominantly by magnetic reconnection between the IMF and the planet's intrinsic magnetic field. Frequent reconnection occurring at Mercury's dayside magnetopause facilitates efficient coupling between the solar wind and the magnetosphere resulting in acceleration and heating of the solar wind particles as they move into the magnetosphere. Here, we present results from recently developed global coupled-fluid simulations of Mercury's magnetosphere (Li et al., 2024, JGR), focusing on the dynamics in the cusp region. The simulations, based on the MHD-AEPIC (MHD with Adaptively Embedded PIC) model, were performed with varied solar wind and IMF conditions. In our simulations, filamentary structures often appear in the cusp region, characterized by significant reductions in magnetic field strength and notable increases in plasma density and pressure. These features resemble those of the so-called "cusp filaments" observed by MESSENGER. By tracking their evolution in our simulation, we demonstrate that cusp filaments are essentially the high-latitude extensions of flux transfer events (FTEs). Additionally, we have examined the spatial distribution and variability of solar wind proton precipitation onto Mercury's surface, which has important implications for surface weathering and exosphere generation. The global precipitation rates in our simulations range between 0.7–2.5×10^25 particles/s, aligning with MESSENGER observations, and they tend to increase with decreasing solar wind Mach number and IMF clock angle. Furthermore, our simulations reveal a notable dawn-dusk asymmetry in proton precipitation patterns with pronounced dawnside precipitation, consistent with asymmetries in magnetopause reconnection occurrence previously predicted by MHD-AEPIC simulations.

## AS25-1362

# Comparative planetary bow shocks

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The study of a planetary shock and especially its structure is crucial to comprehend its microphysics. It is of special interest to understand the solar wind—planet interaction. The solar system offers different cases including magnetized planets like the Earth, Mercury and giant and icy planets but also atmospheric planets without global magnetic field like Venus and Mars. The comparison between the properties of these different types of collisionless shocks as well as associated foreshocks and upstream environments including transients is always instructive on the particle acceleration and energy dissipation mechanisms at work. This review will discuss the state-of-the-art knowledge and some major recent advances on these topics.

## AS25-1377

# Kelvin-Helmholtz instability at the Planetary Magnetospheres and boundaries of the CMEs

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The secondary processes driven by the velocity shear driven Kelvin-Helmholtz Instability (KHI) in the magnetized plasmas have been shown to be important in producing plasma transport and heating from the shocked solar wind into the Earth's magnetosphere (MSP). The plasma transport into the MSP due to KHI has been shown to be strongest during northward interplanetary magnetic field (IMF) via KHI driven low- and mid-latitude reconnection process. During southward IMF, the KHI can further compress current layers and increase the reconnection rate. During southward IMF, KHI can also lead to the periodic generation of the large-scale diamagnetic cavities at mid-and high latitudes. In addition, KHI can seed other instabilities and generate unstable velocity distribution functions, leading to plasma waves, heating and acceleration. KH waves also play important role at Mercury and Mars, and at gas-giants where the fast co-rotating plasma induces additional asymmetries. In this talk, we review the current status of KH studies at Earth, at other planets and the boundaries of the Earth-impacting coronal mass ejections (CMEs) using spacecraft data from multiple missions and numerical simulations.

## AS25-1429

# Magnetic Fluctuations and Turbulence in the Space Environments of Unmagnetized Planets: Insights from Venus and Mars

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The interaction between solar wind and unmagnetized planets, exemplified by Venus and Mars, is a significant issue in planetary sciences. The absence of global intrinsic magnetic fields on these planets results in the formation of complex and unique induced magnetospheric environments due to their interactions with the solar wind. Our study aims to systematically analyze scientific data obtained from planetary space missions to investigate the dynamic magnetic field environments within these induced magnetospheres, with particular emphasis on magnetic fluctuations and multiscale turbulence phenomena. We focus on characterizing the properties, propagation mechanisms, and evolutionary processes of these phenomena. To deepen our understanding of induced magnetospheric environments, we employ a comparative planetology approach, analyzing the differences and similarities between the induced magnetospheres of Venus and Mars. This comparative analysis reveals distinct features and commonalities while exploring the underlying formation mechanisms. In addition, by integrating three-dimensional magnetohydrodynamic simulations, we aim to further uncover the dynamic evolution of these turbulent magnetic environments, thereby providing a theoretical foundation for interpreting the unique space environments of unmagnetized planets. This research not only enhances our understanding of the space environments of unmagnetized planets but also offers critical scientific insights for the design and execution of future deep-space exploration missions.

# A31 Solar Eruptions: Their Origin, Source Region Evolution, and Forecast Implications

## AS25-0086
## Predicting solar eruptions using magnetic field properties

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The evolution of active regions, as captured through magnetic field observations, provides crucial insights into the pre-eruptive conditions that lead to solar eruptions. By individually analysing active regions and parameterising their development, we can better understand the physical state and energetic potential of these regions. Each magnetic parameter offers a unique perspective on the underlying mechanisms driving solar eruptions.

A detailed examination of active region evolution before major solar eruptions enables us to identify critical precursors, significantly improving eruption predicting capabilities. Over the years, extensive research has explored the relationship between active region properties and their eruption productivity. In this talk, we will review these efforts, assess our current understanding, and discuss potential future directions in solar eruption prediction.

## AS25-0109

# Toward Understanding Coronal Mass Ejection Initiation

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Coronal mass ejections (CMEs) are the most energetic explosive phenomenon in our solar system and can release a large quantity of plasma and magnetic flux into the interplanetary space, probably affecting the safety of human high-tech activities in the outer space. To predict CMEs-caused space weather effects, we need to elucidate some fundamental but still puzzled questions, one of which concerns how CMEs are initiated. In this talk, I will present some new observations about the slow-rise precursor and pre-flare activities that can be used to constrain CME initiation models.

## AS25-0124

# MHD instabilities relevant to solar eruptive phenomena

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Solar eruptions involve a combination of non-ideal processes, such as flare reconnection, and ideal MHD instabilities, such as the torus and kink instabilities. The torus instability occurs when the magnetic field external to a flux rope decays sufficiently rapidly with height, and the kink instability sets in when a flux rope possesses more than a critical amount of twist in its magnetic field. In this talk, I will describe the insights we have gained regarding the roles and relative importances of these instabilities from theoretical modelling and observational studies. Continuing to deepen our understanding of these processes will help us understand the onset of solar eruptions, and therefore also help us forecast the associated space weather effects.

## AS25-0129

# Solar Coronal Jets, the Magnetic Flux Changes Leading to Jets, and Implications for Eruptions on Larger Size Scales

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Large-scale solar eruptions often include ejection of a filament, a solar flare, and expulsion of a coronal mass ejection (CME). Such large-scale eruptions are comparatively infrequent, with the moderate level ones (say, GOES M-class events) occurring perhaps once every few days on average during active-activity times. In contrast, solar coronal jets, which are long (~50,000 km), narrow (~10,000 km), transient (~10---20 min) plasma spires with bright bases and that are seen in soft X-rays and EUV, occur much more frequently, likely several hundred times per day independent of large-scale solar activity level. Recent studies indicate that coronal jets are small-scale versions of large-scale eruptions, often produced by eruption of a small-scale "miniflament," that results in a small flare analogous to a larger typical solar flare, and that sometimes produces a CME analogue (a "narrow CME" or "white-light jet"). Under the assumption that jets are small-scale eruptions, their higher occurrence frequency and faster build-up evolution reveals perhaps fundamental aspects of all eruptions that are not as easy to discern in the more-complex magnetic environment and the slower build up to the larger eruptions. For example, several studies show that jets occur at magnetic-flux-cancelation locations, suggesting that this is a key energy build-up and a key triggering process for eruptions of all sizes. This work was supported by NASA's Heliophysics System Observatory Connect (HSOC) Programs, and by the NASA/MSFC Hinode Project.

## AS25-0272

# Studying the origin of high-altitude stealth coronal mass ejections using computational modelling

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Coronal mass ejections (CMEs) are the most energetic events originating from the Sun. They can cause significant and sudden disruption to the magnetic and particulate environment of the heliosphere. Thus, an early warning that a CME has left the Sun is crucial in the current era of space-based technologies. CMEs possessing detectable precursors at the solar surface or lower corona, foe example, the eruption of the associated solar filaments, allow us to predict their arrival. However, many CMEs exhibit no such detectable signatures and are known as "stealth CMEs", which often cause unpredictable geomagnetic disturbances. Our magnetofrictional simulations that capture the global corona's continuous and dynamical evolution over many months demonstrate that the non-potential evolution of the corona leads to the accumulation of magnetic free energy and helicity, which is periodically shed in eruptive events. We find that these events fall into two distinct classes: One set of events is caused by the eruption and ejection of low-lying coronal flux ropes, and they could explain the origin of filament-erupting CMEs. The other events are driven by eruptions of overlying sheared arcades at high altitudes. These are associated with streamer blowouts or stealth CMEs. Further investigation on the second class of events predicts the occurrence of repeated eruptions without clear low-coronal signatures from such arcades, provided that the high, overlying magnetic fieldlines are sufficiently sheared by differential rotation. Thus, our study suggests that magnetofrictional models can, in principle, provide early indication—pre-onset of stealth CMEs, which are challenging to predict.

## AS25-0280

# Magnetic flux emergence leading to solar eruptions

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Active regions form as the result of a period of flux emergence that normally lasts for no more than a few days (typically less than five days). During this time active regions can be prolific producers of coronal mass ejections or produce no eruptions at all. This talk will look at the specific characteristics of those active regions that produce eruptions during their emergence phase and how emerging active regions that are eruptive differ from non-eruptive emerging active regions. The talk will cover the evolution of the emerging active region as seen from the photospheric evolution, and the impact of the photospheric flows and flux emergence on the coronal magnetic field. Implications for the forecasting of coronal mass ejections will also be discussed.

## AS25-0330

# On Sympathetic Extreme Ultraviolet Waves

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Extreme ultraviolet (EUV) waves are large-scale propagating fronts observed on the Sun. Studies of the kinematics of EUV waves revealed that they often consist of two components: a fast-mode wave and a non-wave component. In this study, we present Solar Dynamics Observatory observations of two sympathetic EUV wave events that occurred on December 6, 2021, on the western solar limb. The first coronal mass ejection (CME) originated from NOAA Active Region (AR) 12898 and the associated EUV waves propagated in the northward direction. When the EUV waves reached AR 12902, another CME appeared, which was associated with an EUV wave propagating in the southward direction. The first wave event exhibited two components with speeds being ~500 km/s and ~160 km/s, respectively. Our analysis suggests that the second CME was triggered by the non-wave component, rather than the fast component.

## AS25-0332

# Causes of a Quiescent Filament Eruption

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Solar filaments are the dark elongated structures on the solar surface which are cooler and denser than the surrounding plasma. After loosing their equilibrium, they erupt out of the solar surface producing coronal mass ejections (CMEs). Here, we present a solar filament eruption on 13 July 2015, which was located on the polarity inversion line of a small unnumbered active region. The event is analyzed using the multi-wavelength data of the Atmospheric Imaging Assembly (AIA) and magnetogram of the Helioseismic Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO). The eruption was associated with a clear two-ribbon GOES B7 class flare. The untwisting of the flux rope (FR) is seen during its eruption. The FR erupted successfully with an average speed of ~ 185 km/s and produced a CME with a speed of ~ 552 km/s and a deceleration of ~ 14 m/s2. To understand the origin of the filament eruption, we have computed the magnetic flux at different locations near the filament and conclude that magnetic flux cancellation could be the cause of this eruption. During the eruption, the nearby EUV loops contracted, which is explained in light of existing theories and simulations.

## AS25-0418

# Multi Ribbon Solar Flare and Failed Filament Eruption

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How filaments form and erupt are topics about which solar researchers have wondered for more than a century and they are still open to debate. We present observations of a filament formation, its failed eruption, and the associated flare that occurred in active region (AR) 12740 using data from the Solar Dynamics Observatory (SDO), the Solar-Terrestrial Relations Observatory A (STEREO-A), the Interface Region Imaging Spectrograph (IRIS) and the Learmonth Solar Observatory (LSO) of the National Solar Observatory/ Global Oscillation Network Group (NSO/GONG). Our analysis indicates that the filament was formed by the convergence of fibrils at a location where magnetic flux cancellation was observed. We model the magnetic configuration of the AR using a force-free field approach at the AR scale size. This local model is complemented by a global potential-field source-surface one. Based on the local model, we propose a scenario in which the filament failed eruption and the flare are due to two reconnection processes, one occurring below the erupting filament, leading to a two-ribbon flare, and another one above it between the filament flux-rope configuration and the large-scale closed loops. Our computation of the reconnected magnetic flux added to the erupting flux rope, compared to that of the large-scale field overlying it, allows us to conclude that the latter was large enough to prevent the filament eruption. A similar conjecture can be drawn from the computation of the magnetic tension derived from the global field model.

## AS25-0440

# Onset Mechanism of a Solar Filament Eruption Revealed by NVST, SDO, and STERE-A Observations

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To understand the onset mechanism of solar filaments, we investigated the eruption process of an inverted U-shaped solar filament and two precursory jet-like activities. Using observations from the New Vacuum Solar Telescope (NVST), the Solar Dynamics Observatory (SDO), and the Solar Terrestrial Relations Observatory-Ahead (STEREO-A), we investigated the event from two distinct observational perspectives: on the solar disk using NVST and SDO, and on the solar limb using STEREO-A. We find that two precursor jet-like activities were observed before the eruption, displaying an untwisted rotation. During these two jet-like activities, Y-shaped brightenings, which are newly emerging magnetic flux accompanied by magnetic cancellation, and the formation of newly moving fibrils were identified. Before the filament eruption, it was observed that some moving flows had been ejected from the site as the onset of two jet-like activities, indicating the same physical process as in the two jet-like activities. Extrapolations revealed that the filament was below the height of the decay index of 1.0 and had a strong magnetic field (540 Gauss) and a high twist number (2.4 turns) before the eruption. An apparent rotational motion was observed during the filament eruption. We deduce that the solar filament, exhibiting an inverted U-shape, is a significantly twisted flux rope. The eruption of the filament was initiated by the release of constraining magnetic fields through continuous magnetic reconnection. This reconnection process was caused by the emergence of new magnetic flux.

## AS25-0447

# Magnetic helicity and energy budgets of jet events from an emerging solar active region

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Using photospheric vector magnetograms obtained by the Helioseismic and Magnetic Imager onboard the Solar Dynamics Observatory and a magnetic connectivity-based method, we computed the magnetic helicity and free magnetic energy budgets of a simple bipolar solar active region (AR) during its magnetic flux-emergence phase, which lasted ~47 h. The AR did not produce any coronal mass ejections (CMEs) or flares with an X-ray class above C1.0, but it was the site of 60 jet events during its flux-emergence phase. The helicity and free energy budgets of the AR were below established eruption-related thresholds throughout the interval we studied. However, in addition to their slowly varying evolution, each of the time profiles of the helicity and free energy budgets showed discrete localized peaks, with eight pairs of them occurring at times of jets emanating from the AR. These jets featured larger base areas and longer durations than the other jets of the AR. We estimated, for the first time, the helicity and free magnetic energy changes associated with these eight jets, which were in the ranges of 0.5–7.1×10^40 Mx^2 and 1.1-6.9×10^29 erg, respectively. Although these values are one to two orders of magnitude smaller than those usually associated with CMEs, the relevant percentage changes were significant and ranged from 13% to 76% for the normalized helicity and from 9% to 57% for the normalized free magnetic energy. Our study indicates that jets may occasionally have a significant imprint in the evolution of helicity and free magnetic energy budgets of emerging ARs.

## AS25-0575

# Using (E)UV Emission Properties to Forecast Solar Energetic Events

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Observational case-studies show increased magnetic reorganization, dynamics, and temperature variations in the solar chromosphere and corona before energetic events. Using data from the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory, we investigate whether parameters describing these activities can distinguish flare-imminent from flare-quiet regions.

The AIA Active-Region Patches (AARPs; Dissauer et al. 2023) dataset extracts and downscales AIA time-series data aligned with HMI active region patches to analyze short-lived features and long-term trends in the dynamics of the upper solar atmosphere. Using Nonparametric Discriminant Analysis on over 32,000 samples, we identify differences between flare-imminent and flare-quiet regions, achieving Brier Skill Scores of 0.07–0.33, True Skill Statistics of 0.68–0.82, and Receiver Operating Characteristic Skill Scores above 0.8.

Total emission can perform notably, although mean brightness measures do not, demonstrating the well-known relationship between active region size and flare productivity. Once a region is flare-productive, active-region coronal plasma appears to stay hot. The 94 Å filter provides the most discriminating parameters, indicating that it benefits from sampling multiple physical regimes. Higher-order moments of running-difference images show that flare-imminent regions tend to exhibit short-lived, small-scale brightenings.

Focusing on these small-scale brightening events revealed that flare-imminent brightenings cluster at future flare locations and are co-spatial with reconnection signatures like bald patches and coronal null point fan traces. They align with strong-gradient polarity inversion lines (PILs) and regions of enhanced magnetic energy density. Flare-quiet brightenings appear randomly, occasionally associated with short bald patches and fan traces but away from strong-gradient PILs and high magnetic energy density areas.

## AS25-0632

# Plasma dynamics in eruptive flares

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Solar flares accompanied by filament eruptions and plasma surges involve complex interactions between magnetic reconnection and magnetohydrodynamic instabilities. Despite advances in observations and modeling, the evolution of plasma parameters during these events lacks full understanding. This study employs high-resolution imaging spectroscopy from the Expanded Owens Valley Solar Array (EOVSA) to analyze key plasma parameters in radio sources during such eruptions. We analyzed two X1.0-class solar flares: one on October 2, 2022, accompanied by a filament eruption and coronal mass ejection (CME), and another on May 12, 2024, accompanied by a plasma surge. In both instances, radio bursts occurred during the eruptions. Spatially resolved microwave spectra were analyzed using gyrosynchrotron and free-free emission model to obtain evolving maps of magnetic field strength, thermal plasma density, non-thermal electron density, and the spectral index of accelerated electrons. For the October 2, 2022 event, spectral fitting revealed rapid coronal magnetic field decay during flare's rise and peak phases, correlated with an increase in nonthermal electron density. The May 12, 2024 event showed a magnetic field decrease from the flare's rise phase to its peak, followed by an increase during the decay phase, along with prominent soft-hard-soft spectral evolution of nonthermal electrons. Tracking the temporal evolution of these parameters provides insight into their roles during the eruption process.

## AS25-0715

# Advances in the study of filament eruptions

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Solar filament eruptions are recognized for their significant role in initiating coronal mass ejections (CMEs), making them essential for space weather research. Solar filaments generally remain quiet for several hours or even days before they eventually erupt, necessitating continuous monitoring. This is achieved through the automated identification and tracking of filaments in full-disk solar images. Analysis focused on the continuous observations of several erupting filaments suggests a strong correlation between the area decay rate of the filaments and the speeds of the associated CMEs. The onset time of the CMEs is typically delayed, occurring within two hours after the eruption of the filaments. When filaments erupt, they frequently reveal a helical or flux rope configuration. With the launch of the STEREO mission, 3D reconstruction of eruptive filaments is possible which suggests that filaments evolve in a non-radial manner, exhibiting twisting during the initial eruption phase. The CMEs associated with erupting filaments typically display a three-part structure comprising a bright leading front, a dark cavity, and a high-density core that contains cold filament material. As the CMEs propagate through the interplanetary medium, filaments in rare instances, maintain their "frozen-in" thermal and compositional characteristics, which are recognized in in-situ observations as plasma with high proton and ion density and a low charge state. In this presentation, I will explore various facets of the dynamics of eruptive filaments and present the novel insights provided by observations of the recent space missions i.e. Solar Orbiter, Parker Solar Probe, and Aditya-L1.

## AS25-0912

# Physics-based prediction and understanding of solar eruptions

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Predicting and understanding solar eruptions are crucial in heliophysics and space weather research. We have recently developed a new prediction scheme for large flares, i.e., the κ-scheme, based on the MHD instability theory (Kusano et al. 2020, Science). The κ-scheme can accurately predict large flares' onset and is capable of pinning down the precise location of flares for most events. The successful prediction suggests that the distribution of the twist flux density near the polarity inversion line determines when, where, and how large a flare will occur and that a small-scale reconnection may trigger a large solar flare. However, the κ-scheme is imperfect and fails to predict specific flares. In this talk, I report on the recent progress of the physics-based prediction of solar eruptions, and we discuss what causes failed prediction and what we can learn about the triggering mechanism of solar eruptions from the physics-based prediction. In addition, we present several applications of the κ-scheme for space weather forecasting about the formation of coronal mass ejection (CMEs) and the occurrence of solar energetic particle (SEP) events.

Kusano K, Iju T, Bamba Y, Inoue S. A physics-based method that can predict imminent large solar flares. Science. 369, 587–591 (2020).

## AS25-0927

# Magnetic reconnection events in the Sun observed by the NVST

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New vacuum solar telescope (NVST) is one of the large aperture solar telescopes in the world, located on the shore of Fuxian lake of Yunnan province in China, aiming at serving solar physicists with high resolution photospheric and chromospheric observational data. Magnetic reconnection is a very important process of energy release in Astrophysics. It is widely accepted that the energy on the Sun is released by the magnetic reconnection. However, observational evidence has been relatively rare and typical only partial. Based on the data from NVST and complementary observations from Hinode, SDO, and so on, magnetic reconnection events in the Sun are well observed and studied. In this talk, I will introduce the fine process of small-scale magnetic reconnection in solar flares for detail.

## AS25-0961
# Simulations of solar eruptions

*Vasileios Archontis*[1]

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Solar eruptions is a building block of solar activity and space weather. In this talk, we present 3D numerical simulations of magnetic flux emergence in a highly stratified solar atmosphere, which show the onset and the dynamic evolution of solar eruptions. We show how processes, such as shearing, magnetic reconnection and flux cancellation could drive the onset of the eruptions. We discuss how these eruptions may occur on different spatial scales and how they can drive jets or develop into CME-like eruptions.

## AS25-1137

# The Magnetic Origin of Solar Coronal Jets and Campfires: SDO and Solar Orbiter Observations

*Navdeep Panesar[1], Alphonse Sterling[2], Ronald Moore[3], Sanjiv Tiwari[4], Viggo Hansteen[4], David Berghmans[5], Mark Cheung[6], Daniel Muller[7], Frederic Auchere[8], Andrei Zhukov[5]*

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We present the magnetic origin of different types of campfires and coronal jets, using line-of-sight magnetograms from the Solar Dynamics Observatory (SDO)/Helioseismic and Magnetic Imager, together with extreme ultraviolet images from the Solar Orbiter/Extreme Ultraviolet Imager and from the SDO/Atmospheric Imaging Assembly. We find that (i) both campfires and coronal jets reside above neutral lines and they often appear at sites of magnetic flux cancelation between a majority-polarity magnetic flux patch and a merging minority-polarity flux patch, with a flux cancelation rate of $\sim 10^{18}$ Mx $hr^{-1}$ (ii) The majority of campfire brightenings are preceded by eruption of a cool-plasma structure, analogous to erupting minifilament that precede coronal jets." Our observations suggest that (a) the presence of magnetic flux ropes may be ubiquitous in the solar atmosphere and not limited to coronal jets and larger-scale eruptions that make CMEs, and (b) magnetic flux cancelation, most likely accompanied with magnetic reconnection in the lower solar atmosphere, is the fundamental process for the formation and triggering of most solar campfires and coronal jets. Finally, we compare fine-scale jets (i.e., campfires and similar jet-like features that are smaller than typical coronal jets) with results found from a Bifrost MHD simulation.

## AS25-1153

# Helioseismic Diagnostics of Shearing and Rotational Motions in Emerging Active Regions and Forecasting of Solar Eruptions

*Alexander Kosovichev*[1]

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Emerging magnetic flux and vortical and shearing surface and subsurface flows are among the primary drivers of solar eruptive activity. We investigate the evolution of subsurface flows during the emergence and the active phase of sunspot regions and their relationship to the initiation of eruptions using time-distance helioseismology data. The study is performed by tracking active region areas during their passage on the solar disk, including the periods before and after the emergence observed by the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO). The flow maps, covering the range of depths from 0 to 19 Mm, are obtained using eight-hour Dopplergram data series with one-hour shifts. We present an analysis of emerging active regions of various types, including the super-active delta-type sunspot regions and regions with the reverse polarity order (`anti-Hale active regions'). The results reveal strong vortical and shearing flows during the emergence of magnetic flux, as well as the formation of large-scale converging flow patterns around developing active regions, predominantly in the top 4 Mm deep layers. Our analysis shows a significant correlation

## AS25-1174

# Segmentation and characterization of solar coronal structures: Comparing the efficiency of deep learning and traditional machine learning methods

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Segmentation and characterization of solar coronal structures are essential for advancing our understanding of the solar atmosphere and accurately identifying key regions, such as active regions and coronal holes, which are precursors to phenomena like solar flares and coronal mass ejections (CMEs). In this study, we investigate various complementary approaches to automate this process. First, we employ a previously presented deep learning-based U-Net architecture tailored for segmenting and characterizing solar coronal structures, which has proven to be accurate but challenging to deploy due to its large number of trainable parameters. Then, we develop a lightweight algorithm aimed at optimizing resource efficiency, consisting of classical computer vision techniques like thresholding and morphological filtering. We lastly develop an ultra-light deep learning-based algorithm based on YOLO (You Only Look Once) to perform detection. The performance of our methods is thoroughly evaluated using metrics such as Dice score and Intersection over Union (IoU), with comparisons made against state-of-the-art methods. The framework that best balances segmentation and detection performance with computational efficiency will be selected for integration into a prototype designed to support future space exploration missions. Finally, we propose a set of carefully designed hand-crafted features to represent and characterize the resulting segmentations. These representations are analyzed using unsupervised clustering techniques, such as t-SNE, to distinguish solar coronal structures, such as active regions, coronal holes and bright points. This work is part of the project AutomaticS in spAce exPloration “ASAP” funded by the European Union under HORIZON Research and Innovation Action (GA no.101082633).

## AS25-1211

# Semantic segmentation of SHARP vector magnetic field maps using Kohonen Self-Organizing Maps

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Based on synoptic observations from the Solar Dynamics Observatory's (SDO) Helioseismic and Magnetic Imager (HMI), the Space-weather HMI Active Region Patches (SHARP) dataset—an extensive archive of images and empirical parameters—is a valuable resource for studying solar flare precursors and developing flare prediction strategies. Vector magnetic field (VMF) maps contain a wealth of information about the complexity and evolution of the magnetic structure of the active region, which is essential for understanding the onset of eruptive phenomena. In this work, we explore the application of Kohonen Self-Organizing Maps (SOMs), an unsupervised machine learning technique, for semantic segmentation of SHARP VMF maps to facilitate the study of active region structure and evolution. SOMs can capture complex, non-linear relationships between pixels while preserving morphological and topological differences. This is achieved through competitive learning, where similar input data points are mapped to nearby neurons on a grid, forming clusters. In addition, SOM segmentation is used to identify unreliable VMF values that may arise due to the limitations of the inversion process, allowing them to be excluded from further analysis. The segmentation results are then used to automatically classify magnetic features for further investigation. This approach provides an interpretable visualization of the data distribution and helps to identify distinct patterns in the magnetic field structure, such as emerging flux regions and eruption precursors, for subsequent analysis.

## AS25-1378

# Magnetic Sources of Coronal Mass Ejections and Coronal Bright Dots

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We investigate the photospheric magnetic field connections underlying the largest and smallest solar explosions—coronal mass ejections (CMEs) and fine-scale coronal bright dots. Recently, bright dots of sub-arcsecond sizes with lifetimes of less than a minute were observed using Solar Orbiter's EUI data within an emerging flux region (inside a solar X-ray/EUV bright point). In the first part of the presentation, we use SDO/HMI vector magnetograms to compute several magnetic non-potentiality parameters of the source active regions (ARs) of CMEs. Our results show that the upper limit of CME speed can be more accurately predicted using an AR magnetic-twist parameter and with the corresponding free-magnetic-energy proxy. In the second part of the presentation, using EUI/HRI and SDO/AIA observations along with Bifrost MHD simulations, we demonstrate that the smallest EUV bright dots in emerging flux regions originate from bursts of magnetic reconnection between newly emerging and pre-existing magnetic fields. In approximately half of the studied cases, HMI photospheric magnetograms reveal mixed-polarity magnetic flux, which could be linked to the submergence of the lower reconnected loops. Additionally, about half of these bright dots exhibit jet-like extensions. Our findings suggest that the magnetic explosions driving EUV bright dots may be fundamentally similar in nature to those responsible for CMEs, highlighting a possible continuum in reconnection-driven explosive events across vastly different spatial and energetic scales.

## A32 Solar Cycle 25 and Comparisons to Previous Cycles

### AS25-0038

# Information theory based system level Babcock-Leighton flux transport model-data comparisons

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System level Babcock-Leighton flux transport model-data comparisons are performed using information theory. The model is run with maximum meridional flow speed of 16.5 m/s with the flow speed systematically varied by 20% (BLFT20) and 50% (BLFT50). Overall, the comparisons show that the models qualitatively capture much of the information flows among the toroidal field (sunspot number), polar field, and meridional flow. BLFT20 generally compares better than BLFT50 suggesting that meridional flow variation of 20% may be more realistic than 50\%. However, the information flow from the meridional flow to the polar field is captured better in BLFT50. There is more information flow from the sunspot number to the polar field than the other way around in BLFT20 and observations. The information flow from the polar field to the sunspot number peaks at lag times (tau) ~2 year and 7–9 years. The results can shed light to the nature of the Sun's magnetic memory, and the diffusive/dissipative processes and advection in the turbulent flux transport at the Sun.

## AS25-0299

# Physics-based models studying solar magnetic cycles and their predictive capability

*Prantika Bhowmik*[1]

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Solar variability governs the electromagnetic, radiative, and particulate environment in the heliosphere, and it is closely associated with and dominated by the sunspot cycle. The sunspots are one of the primary manifestations of the Sun's magnetic field. Thus, our understanding of the origin and spatio-temporal evolution of the solar magnetic field through sunspot cycles will help the community to probe and predict solar magnetic variability. The dipolar field during the cycle minimum is one of the best precursors for sunspot cycle prediction. However, the intrinsic stochastic nature of the solar convection zone limits the range of predictability to half a solar cycle. Recently, a new methodology has been devised by combining an observational data-driven surface flux transport model and an interior dynamo model to extend the prediction time window to a decadal scale. This new methodology has been validated by performing a century-scale data-driven simulation that successfully reproduced the past observation—the first of its kind. Subsequently, this technique was employed to predict sunspot cycle 25 while considering various possible uncertainties. This work, along with other contemporary works in the last decade, has paved the path towards a better understanding of solar cycle variability and improving its prediction ability while solely relying on the physics of the solar interior and surface magnetic field.

## AS25-0477

# Ionospheric model performance in solar cycles 24 and 25: How did we do?

*David Themens*[1], *Emma-Claire Gurney*[1], *Matthew Brown*[1], *Sean Elvidge*[1]

[1] *University of Birmingham, Space Environment and Radio Engineering Group, Birmingham, United Kingdom*

Solar activity plays a dominant role in the dynamics and climatology of the ionosphere-thermosphere system. Complex feedback mechanisms between increases in photoionization and changes in thermospheric composition and transport with solar activity significantly complicate the task of building reliable empirical ionospheric climatologies to support space weather operations. In this presentation, we will explore the competing mechanisms controlling the ionospheric response to changes in solar activity using comparisons between Solar Cycles 24 and 25. To this end, a largescale model validation on solar cycle timescales will be presented spanning a wide range of ionospheric models including: the Empirical Canadian High Arctic Ionospheric Model (E-CHAIM), the extended Whole Atmosphere Community Climate Model (WACCM-X) and its Specified Dynamics counterpart (WACCM-X SD), the Thermosphere-Ionosphere-Magnetosphere General Circulation Model (TIE-GCM), and the International Reference Ionosphere. Comparisons will be drawn between the responses of each model to solar activity over the past two solar cycles, focusing on ionospheric observations in the polar cap and European mid-latitude regions.

## AS25-0641

# Evolution of Large-Scale EUV Coronal Structures Over Solar Cycles: Insights from Observations and Future Perspectives

*Matthew West*[1]

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The solar corona undergoes significant structural evolution over the course of the solar cycle, driven by changes in the Sun's magnetic field. In this presentation, I will examine the evolution of the inner and middle corona throughout Solar Cycle 24 using extreme ultraviolet (EUV) observations. Through an analysis of EUV intensity variations, I will investigate the evolution of on-disk coronal features and extended structures at different heights above the solar surface. I will highlight the differences between equatorial and polar regions, their evolution through different cycle phases, and how they correlate with sunspot number variations.

Looking ahead, I will discuss how upcoming operational missions, such as ESA's Vigil and NOAA's GOES and SWFO missions, will advance our ability to monitor and analyze coronal variability in near real-time. By providing continuous observations from both Sun-Earth line and off-axis vantage points, these missions will offer improved spatial and temporal coverage, enabling a more comprehensive understanding of coronal dynamics across solar cycles. These observations will be crucial for improving solar activity models and advancing long-term space weather forecasting.

## AS25-0819

# Solar Cycle 25 and Comparisons to Previous Cycles

*William Chaplin*[1]

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In this invited talk, I will give a brief overview on how the current solar activity cycle 25 compares to previous cycles, including insights from helioseismology covering the most recent cycles.

## AS25-0904

# Inferring the global solar interior currents from the solar coronal surface magnetic fields

*Bogyeong Kim*[1], *Yu Yi*[2]

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We analyzed the solar coronal magnetic field during Solar Cycles 21–25 (1976–2024) using spherical harmonics decomposition of the Wilcox Solar Observatory (WSO) data. By separating the field into axis-symmetric and non-axis-symmetric components, we found that the phase of the octupole closely follows that of the dipole, showing a strong correlation. The axis-symmetric components of the dipole and octupole exhibit a remarkably high degree of phase similarity. Additionally, at the equator, the absolute magnitude of the axis-symmetric component is larger for the dipole, and their phases are opposite. These results suggest that instead of treating the solar magnetic field primarily as a dipole, considering both the axis-symmetric and non-axis-symmetric components of the octupole could offer new insights into the solar dynamo mechanism. The multipole analysis further reveals that the octupole component has a comparable strength to the quadrupole and is significantly more dominant than higher-order terms, emphasizing its importance in dynamo studies. Our findings indicate that the dipole and octupole components appear together, and their interaction may influence the internal current dynamics responsible for the Sun's magnetic field reversals. By incorporating the octupole contribution, we propose an improved dynamo model that better aligns with observed solar magnetic field variations, addressing existing discrepancies between theory and observation.

## AS25-0938

# Polar Cap Brightenings and Polar Coronal Holes: Origin of the Fast Solar Wind

*Ken'ichi Fujiki*[1], *Kazumasa Iwai*[1]

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Polar cap brightening refers to enhancements in brightness observed in microwave data around the solar polar regions. This phenomenon has been extensively studied using the Nobeyama Radioheliograph (NoRH) at a frequency of 17 GHz, particularly in relation to solar cycle variations and the structural characteristics of the solar corona. Previous studies have suggested a close association between polar cap brightening and the distribution of coronal holes.

In this study, we compare the long-term variations in the radio brightness of the solar polar regions observed by NoRH, the polar solar wind speed derived from interplanetary scintillation (IPS) observations conducted at the Institute for Space–Earth Environmental Research (ISEE), Nagoya University, and the coronal hole distribution inferred from potential field calculations using ground-based magnetic field observations. The analysis covers the period from 1992 to 2017.

Our results reveal a strong correlation between the polar solar wind speed (V) and the brightness temperature (Tb). The correlation coefficient is 0.91 in the northern polar region and 0.83 in the southern polar region, confirming a significant relationship. Furthermore, we confirm that the correlation between V and Tb is stronger than that between V and other parameters, such as the polar magnetic field strength (B) or the expansion factor of the magnetic flux tube (f). These findings suggest that Tb serves as a more direct and reliable indicator of solar wind speed compared to 1/f or B/f, which are widely recognized in theoretical and empirical studies.

## AS25-0998

# Long term evolution of coronal mass ejections inferred by galactic cosmic rays modulation

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Solar activity varies in a wide range of time scales, from subseconds to centuries, as shown by solar wind in-situ measurements and cosmogenesis nuclei stored in polar ice, respectively. These nuclei are generated in the atmosphere by galactic cosmic rays (GCR), this is a quasi- constant and isotropic flux of charged particles filling the local interstellar medium. Inside the heliosphere, the GCR flux is modulated by the solar activity, decreasing the GCR flux during periods of high activity and vice versa. This modulation is mainly caused by Coronal Mass Ejections (CMEs) and high-speed streamers (HSS). Recently, high-sensitivity GCR observations carried out with the High Altitude Water Cherenkov (HAWC) array have shown that magnetic flux ropes (MFR) embebed in CMEs generate GCR anisotropies that may play a major role in the long-term GCR modulation. Therefore, GCR modulation observed at ground level during decades may give us valuable information about the long-term evolution of CMEs and HSS. In this work, we present the relationship between CME characteristics and GCR over the solar cycles 23, 24 and part of 25; the evidence of the GCR anisotropies generated by the MFR; and their implications on the long-term evolution of CMEs.

## AS25-1085

# Photospheric Observations of the Solar Magnetic Field Over Solar Cycles 21–25

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The solar magnetic field undergoes a global magnetic polarity change every ~11 years. As is well known, the leading polarities in the north and south hemispheres oppose each other and alternate every sunspot cycle (Hale's law), and leading-polarity sunspots generally emerge at lower latitudes than their trailing-polarity counterparts (Joy's law). The net result of bipole flux emergence and surface flux transport is predominantly leading-polarity flux cancellation at low latitudes and trailing-polarity flux migration to the poles. Thus, the polar fields follow a ~11-year cycle in approximate anti-phase with the activity cycle, ending each cycle with fully developed polar fields of trailing sunspot polarity in each hemisphere. I will use magnetograms from multiple sources, full-disk and high-resolution (SOLIS/VSM, GONG, Hinode/SOT/SP, WSO), to trace the polarity reversal of the solar field from active to polar latitudes by analyzing patterns of active region emergence and surface flux transport. Cycles 21–25 will be covered in detail, including the premature cessation of hemispheric flux change and weakened polar fields of cycle 23, the large hemispheric flux reversals and asymmetric polar field changes of cycle 24, and the ongoing polar field development following the cycle 25 reversal.

## AS25-1123

# Statistical studies of coronal holes through the solar cycles

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One of the most fundamental properties controlling activity on the Sun is its magnetic field: the interplay between closed and open fields has an enormous effect on coronal mass ejections and the solar wind (CMEs). Coronal holes (CHs) are the regions of open, unipolar magnetic fields where high-speed solar wind stream particles are accelerated into interplanetary space, thus playing a crucial role in heliophysics as one of the main drivers of geomagnetic activity. Active regions (ARs), areas with a strong closed magnetic field, host many eruptive events such as flares, filament/prominence eruptions, CMEs, etc. In this study, we present a statistical analysis of equatorial coronal holes (ECHs) and ARs for four solar cycles. We used a synoptic map method to measure the location areas of the coronal holes and active regions. We compare the number of ECHs and ARs, separations between their centroids, solar wind speed, pressure, and the number of intense geomagnetic storm (IGS) data over these four cycles. Also, we study odd-even trends in the relation between the wind properties and the numbers of close AR and ECH. In addition, we present an analysis of polar coronal holes to discern how the polar region evolved from the extreme ultraviolet and X-ray view for solar cycles 23 and 24. We show the evolution of growth and decay of the polar coronal holes through the solar cycles and how the polar coronal hole boundaries are different in the two epochs.

## AS25-1191

# Tracking solar variability with the Global Solar Activity data portal

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The complexity and multi-scale nature of solar dynamics and the shortage of observational data limit our ability to build a model that can describe the modulation of solar activity for past, current, and future times. At present, despite the availability of a large amount of observations from various data sources, the data repositories are scattered, and some historical data are in danger of being lost. Therefore, we have initiated the development of the Global Solar Activity (GSA) Data Portal, which accumulates diverse data relevant to global solar dynamics. The data portal includes observations from space- and ground-based instruments, helioseismic inferences, and processed data. The portal allows easy access to a wide range of data supported by a quick look visualization and description to perform data analysis through cycles of solar activity, as well as the development of new approaches to predict it. For example, we present an analysis of the properties of supergranulation, a key element of solar dynamics, during the previous solar cycles and the current cycle 25 using SDO/HMI observations. This presentation discusses different approaches to identifying supergranulation and tracking its evolution over the activity cycles. We also discuss the extension of this study and polar regions by utilizing the Hinode/SOT observations.

## AS25-1283

# Predicting geomagnetic activity cycles

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Most solar cycle predictions focus on predicting the 11-year sunspot cycle, while space weather and geomagnetic activity predictions are largely made for short time scales, from hours up to a month. Here, we aim to predict geomagnetic activity in the solar cycle time scale. We use a 180-year composite of the geomagnetic aa index and fit each aa cycle between two successive sunspot minima with a parameterized asymmetric Gaussian curve. We show that this curve can be represented using only two free parameters and the model closely depicts the cyclic behavior of the aa index at about a 5-year time scale. However, it is unable to accurately represent shorter term variability.

We show how the two parameters can be forecasted using past aa values and a recently developed sunspot prediction model. Employing these estimated parameter values, we hindcast each past aa cycle from Solar Cycle 10 (SC10) onwards and make a prediction for the ongoing SC25, also estimating the uncertainties using a leave-one-out cross-validation methodology. Each cycle prediction is made at the time of minimum aa starting the respective cycle.

For SC25, our prediction gives the (5-year smoothed) aa maximum of 21 ± 3 nT, which is slightly higher than, e.g., in SC24 (19 nT). However, our prediction suggests that the overall aa cycle maximum was already reached rather early in the cycle in July 2022. This suggests that SC25, similarly to SC11 and SC13, will probably not have a strong, long-lasting peak of geomagnetic activity in the late declining phase.

## AS25-1294

# Dynamics of Subsurface Large-Scale Convection, Zonal, and Meridional Flows Inferred by Local Helioseismology During Solar Cycles 24 and 25

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Using observational data from the SDO/HMI time-distance helioseismology pipeline covering the period from May 2010 to August 2024, we study the large-scale convection, differential rotation, and meridional circulation in subsurface layers of the Sun. The spatial spectra of solar convection decomposed into spherical harmonics reveal a superposition of differently scaled flows varying with depth and time—supergranulation with a horizontal size of 20–50 Mm and giant-scale flows of 80–150 Mm. The giant-scale velocity spectrum indicates the formation of meridionally elongated (possibly banana-shaped) structures. The integrated spectral power of the flows is anti-correlated with the solar activity level in the near-surface layers and positively correlated with it in deeper layers. The data reveal the "extended" 22-year cycle of zonal flows migrating with latitude ("torsional oscillations") and the corresponding variations of subsurface meridional flows, exhibiting a North-South asymmetry. A high-latitude secondary zonal flow observed in the subsurface layers at the epoch of the maximum of Solar Cycle 25 manifests an early signature of Cycle 26.

## AS25-1323

# Parker Solar Probe: Half a Solar Cycle of Unprecedented Solar Exploration

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For half a solar cycle, NASA's Parker Solar Probe has been transforming our understanding of the Sun, offering groundbreaking insights into its dynamic and complex atmosphere. Having successfully completed 22 of its planned 24 orbits during the prime science phase, the mission continues to deliver data of unparalleled quality, captivating both the global scientific community and the public. These observations have led to paradigm-shifting discoveries, firmly establishing Parker Solar Probe as one of the most successful heliophysics missions in history. With the spacecraft and its instruments operating at peak performance, the mission's future beyond the prime phase holds extraordinary promise. This presentation will highlight key discoveries to date, tracing the evolution of the solar atmosphere from the quiet of solar minimum to the intensity of solar maximum during Solar Cycle 25. Additionally, I will discuss the exciting prospects for Parker Solar Probe as it ventures toward an unprecedented exploration of the declining phase of the solar cycle—offering a front-row seat to the Sun's ever-changing behavior.

## AS25-1412

# Solar cycle effects on the solar wind, coronal mass ejections, and their Interaction with the local interstellar medium

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Solar cycle has a profound effect on the solar wind (SW) propagation through the heliosphere until it ultimately collides with the local interstellar medium (LISM). Solar minima and maxima are the extreme periods within approximately 11-year solar cycles. The minima are characterized by the least solar activity and latitudinal extent of the slow wind region. The maxima, on the other hand, have a large number of sunspots, solar flares, and coronal mass ejections (CMEs), where slow-wind streams reach the Sun's poles, with a prominent variability in the high-speed/low-density and low-speed /high density flows. Non-alignment between the Sun's rotation and magnetic axes create so-called corotating interaction regions (CIRs). There can be substantial differences also between solar cycles. We present a general overview of the SW features associated with solar activity maxima and minima. We also present the results of numerical simulations of solar cycle effects on the SW propagation using observational data as the boundary conditions. While we initially discuss the results governed by the Ulysses data, we make a particular emphasis on the simulations driven by the synchronic photospheric magnetograms covering the time interval overlapping with solar cycles 24 and 25. In combination with the Open Flux transport (OFT) and Wang-Sheeley-Arge models, they allow us to analyze the SW propagation and compare simulation results with in situ observations. Examples of simulating CME propagation are also given. Finally, a few basic effects of the SW interaction with the LISM flow are discussed.

## AS25-1415

# Solar Cycle 25 and Solar Cycle-Dependence of Geomagnetic Disturbances and Their Role in Driving GICs in the Electric Power Grid

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Geomagnetic disturbances (GMD) are excited in the geospace system by a range of solar wind and related internal drivers, and whose occurrence rates change on timescales from minutes and hours, to days, months, and years, and through the solar cycle, and indeed from solar cycle to solar cycle. Here we use data from the Canadian Array for Real-time Investigations of Magnetic Activity (CARISMA; www.carisma.ca) spanning more than 35 years of operations to review a variety of solar wind drivers of GMD, and examine the characteristics of the resulting GMD on the ground. In addition, we use a province-scale model of the Alberta electric power grid in Canada to examine the geomagnetically induced currents (GICs) which result from these GMD. We focus on large geomagnetic storms during solar cycle 25, and highlight the characteristics of a number of drivers of the large GMD which also result in large GICs. We further place these characteristics from solar cycle 25 in the context of the historical measurements from CARISMA and whose dataset spans a number of solar cycles. Specifically, we derive the statistics of 1-in-100 year storm magnitudes of not only magnetic but also electric fields using magneto-telluric determined ground impedance tensors. Finally, we provide some perspectives on the interplay between the magnitudes and spatiotemporal variations of the GMD and electric fields on the GICs which result in the electric power grid, including the effects arising from the non-uniform topologies of the networks of conducting infrastructure which comprise real-world electric power grids.

## AS25-1438
# Helioseismic probes of the solar cycle

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Helioseismology, the study of solar acoustic modes, provides a powerful tool for inferring the large-scale flows that drive the solar dynamo, differential rotation and meridional circulation. Both of these flows exhibit small temporal variations, particularly in connection with the solar butterfly diagram, which tracks the evolving distribution of magnetic activity at mid and low latitudes over the solar cycle. The origin of the high-latitude variations in solar rotation remains an interesting question. We find that the high-latitude inertial modes may serve as a key probe of the dynamics above 60° latitude, offering insights into their interactions with differential rotation and the magnetic field. Recent measurements of the m=1 high-latitude mode over the last five solar cycles provide new constraints on its long-term variability and possible links to solar cycle modulation.

# A33/A34 Electromagnetic induction: Methodology, Data, Modelling, and Inversion / Electromagnetic methods for exploration: geothermal energy, groundwater, mineral resources, etc.

## AS25-0062

## Unveiling the subsurface structure of Kelud Volcano through 2-D magnetotelluric analysis

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Indonesia, located within the Pacific Ring of Fire, is highly prone to natural disasters such as earthquakes and volcanic eruptions due to its tectonic and volcanic activity. The islands of Sumatra, Java, and Sulawesi experience the highest levels of volcanic activity in this region. Kelud Volcano, an active stratovolcano in Kediri, East Java, underwent an effusive eruption in 2007, forming a lava dome in its crater lake. This study aims to investigate the subsurface resistivity distribution of the Kelud volcano using the magnetotelluric method. A grid system with 10 measurement points, spaced approximately 250 meters apart, was deployed across the summit area, complemented by a long profile crossing the summit. Data collection utilized the Phoenix MTU-5 system, recording five components of the electric and magnetic fields within a frequency range of 320 Hz to 1 Hz. The 2D inversion of the MT data revealed that subsurface resistivity near Kelud Volcano ranges from 1 to 100 ohm.m. A low-resistivity clay cap, indicative of a hydrothermal system, was detected at a depth of 1000 meters west of the summit, with values between 1 and 10 ohm.m. Meanwhile, a high-resistivity conduit structure, exceeding 100 ohm.m, was identified in the summit's central region. These findings provide valuable insights into the volcano's subsurface characteristics.

**Keywords**

Kelud Volcano, Inversion modelling, Magnetotelluric, Resistivity

## AS25-0077

# Electromagnetic modeling kernels in the exascale computing era

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The rapid evolution of computational geosciences has significantly advanced geophysical imaging, with electromagnetic (EM) methods playing a crucial role in resource exploration and environmental studies. The Exascale computing era offers unprecedented opportunities for enhancing the speed and accuracy of EM simulations; however, key challenges remain in terms of scalability, fault tolerance, and the efficient implementation of high-performance numerical algorithms. Europe is at the forefront of this transition, with substantial investments in EuroHPC infrastructures such as LUMI and MareNostrum-V, a pre-Exascale computing system.

In this work, we present our experience in the development and optimization of PETGEM, a parallel high-order finite element EM modeling code, for execution on MareNostrum-V. Our efforts focus on adapting PETGEM to leverage the computational power of modern architectures, addressing issues related to parallel efficiency, memory management, and solver performance. These advancements not only improve the scalability of EM modeling but also provide a robust framework for high-fidelity imaging in geophysical applications. Additionally, we demonstrate the capability of PETGEM for large-scale EM modeling using experimental data, showcasing its ability to handle complex real-world scenarios with high computational efficiency. By fostering collaboration with the geophysics community, we aim to bridge the gap between high-performance computing and EM imaging, facilitating more accurate and computationally efficient subsurface exploration.

## AS25-0080

# Comparison and interpretation of two regional-scale magnetotelluric sections in Hungary

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We have created large-scale magnetotelluric sections which cross the country from one border to the other to inspect our region from a new perspective. For this purpose, archived MT data were combined with new field measurements in case of data gaps to form sections and provide nearly uniform station density along the profiles (approx. 1 MT sounding per every 2 km).

These kind of MT sections are the MTOA-02 and MTOA-03 sections which cross the western part of Hungary (Transdanubia) in NW-SE directions. Both sections consist of more than 100 MT soundings with approximately uniform distance between the individual measurements. This allows to form more than 200 km long sections which pass over the main tectonic units of the region (e.g.: Austroalpine Unit, Transdanubian Range Unit, Mid-Hungarian Megaunit, Tisza Megaunit). Comparing the resistivity anomalies on the magnetotelluric sections helps to differentiate local inhomogeneities and structural boundaries which may contribute to the better understanding of the regional geology.

Complex interpretation of the magnetotelluric data included the observation of raw magnetotelluric data, 1D and 2D inversions as well as taking into consideration additional information from gravity, geomagnetism and geologic maps. Seismic data were also used to aid the interpretation of the resistivity anomalies of the upper region where it was available.

## AS25-0140

# Surfing the biggest waves – geomagnetic storms boost magnetotelluric data quality

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A series of powerful geomagnetic storms hit the Earth in May 2024 and brought parts of human infrastructure such as power grids in Europe close to failure. The event was classified as a storm of the highest class G5 reaching a Kp=9. At that time, we carried out a magnetotelluric (MT) survey in the German Kupferschiefer district close to the city of Spremberg and the Welzow-Süd open-pit coal mine in the framework of the EU funded project VECTOR. The region is affected by electromagnetic noise from various sources including mining activities and dense railway networks, power lines and the city of Spremberg. In May, we deployed 22 MT stations along two profiles of 10 and 5 km lengths. Time-series data were sampled continuously with 1.25 kHz and additionally for 10 mins during night with 6.25 and 25 kHz. Throughout the field survey, the permanent remote reference station in Wittstock was operated with the same settings. First results using the remote reference technique together with notch filters show reasonable data quality in a period band from $10^{-4}$ to 1s for geomagnetically quiet times. During the storms, quality of the transfer functions is generally higher with improved MT curves for two more decades, to periods of 100s. But even shorter periods between $10^{-4}$ and $10^{-3}$s might benefit. We demonstrate the influence of the solar storm on the data quality, analyse spectral properties in stormy and quiet times, discuss the importance of the reference site and general aspects of data processing in noisy environments.

## AS25-0143

# Impact of noise on the inverted model in a Gauss-Newton-based 3D CSEM inversion

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This study investigates the impact of noise in data on the inverted model estimated using a Gauss-Newton-based 3-D controlled-source electromagnetic (CSEM) inversion algorithm. The influence of noise is analysed for different noise types and regularisation strategies. The results show that random noise propagates during advanced inversion iteration when regularisation parameters are reduced to allow an update of finer detail in the model. Further, this noise impacts the shallower subsurface comparatively more than the deeper part. Furthermore, it may have minimal effect on estimating important anomalies, as these depend on smoother data components. Numerical experiments also indicate that geological anomalies, such as vertical dykes or fractures, introduce significant challenges for isotropic inversion in terms of convergence and data fitting, even when the subsurface is isotropic. In contrast, anisotropic inversion handles such anomalies well, offering faster convergence and better data fitting. Anisotropic inversion is essential for cases involving an anisotropic host medium, as isotropic inversion introduces substantial artefacts and produces a poor data fit. Numerical experiments exhibit that anisotropic inversion generally yields better data fitting and faster convergence, even for isotropic subsurfaces. However, given the varying sensitivity of CSEM data to thin resistive bodies, caution should be exercised while calculating anisotropy from anisotropic inversion results.

## AS25-0200

# New time-lapse inversion method using structural coupling

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Continuous geophysical data acquisition and time-lapse inversion are essential for effective subsurface monitoring. Conventional time-lapse inversion methods, such as parallel inversion (e.g., Miller et al., 2008), sequential inversion (e.g., Asnaashari et al., 2014), and differential inversion (e.g., Bretaudeau et al., 2021), have been widely employed. However, these methods are highly sensitive to variations in observation layouts, often leading to artificial temporal changes (Kim et al., 2009; Karaoulis et al., 2010). Misinterpretation of apparent temporal variations can lead to erroneous conclusions about subsurface processes, posing a significant obstacle to the fundamental objective of understanding subsurface dynamics.

To overcome these limitations, we propose a new time-lapse inversion approach incorporating the structural coupling method. This technique, commonly used in joint inversion of multi-geophysical datasets, enhances correlation between physical models while allowing partial structural differences to fit individual datasets. By integrating this concept into time-lapse inversion, we enforce stronger consistency across temporal models, effectively suppressing apparent temporal variations.

We developed a time-lapse inversion code with structural coupling using Group Lasso (Yuan & Lin, 2005; Utsugi, submitted) and performed synthetic tests under varying observation layouts. The results demonstrate that our method significantly mitigates artificial temporal changes compared to conventional approaches, thereby improving the accuracy of time-dependent change detection. By mitigating the influence of apparent temporal variations, the proposed method will contribute to a more reliable understanding of subsurface dynamics, advancing the field of geophysical monitoring.

## AS25-0293

# Transdimensional Bayesian inversion of 2D magnetotelluric data with axial anisotropy

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Magnetotelluric (MT) data inversion using isotropic resistivity models can lead to significant misinterpretation in the presence of anisotropic structures. The traditional anisotropic inversion methods, which are typically based on gradient-based minimization, offer computational efficiency but are prone to getting trapped in local minima. Moreover, the reliance on linearization and the subjective choices of model regularization for constraining structure and anisotropy complexity does not fully capture the non-linear relationship between the observed data and the model. Also, the uncertainty in the estimated parameters is either limited or missing. To address these issues, we present a transdimensional Bayesian inversion framework for inverting MT data in axial anisotropic 2D media. In this approach, the number of model parameters defining the model is treated as an unknown and are estimated within the inversion process. The estimate of the uncertainty in the model parameters is derived from an ensemble of models that satisfy the observed data with the error bounds. We assess the performance of the proposed algorithm on both isotropic and axial anisotropic synthetic datasets. Application to the COPROD2 benchmark dataset not only successfully images the North American Central Plains (NACP) and TOBE conductive anomalies but also predicts an anisotropy ratio of two orders of magnitude, in agreement with laboratory findings.

## AS25-0341

# Seafloor magnetotelluric monitoring to investigate potential fluid migration associated with slow slip events in the Northern Hikurangi Subduction Zone

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Slow Slip Events (SSEs) may facilitate stress concentration on fault lock patches and could serve as indicators to nucleation process of large earthquakes at depth (Kato et al., 2012; Obara and Kato, 2016). However, their triggering mechanisms remain poorly understood. While rock experiements, numerical simulations, and geophysical imaging suggests that fluid migration at depth is a key factor in initiating SSEs, direct observations of the fluid movement before, during, and after these events are lacking. To address this gap, we've started a seafloor magnetotelluric (MT) montoring study in the Northern Hikurangi Subduction Zone. Over the first year, data collected on three seafloor sites was recoverd in October, 2024. We preliminarily analyzed the time series and estimated the MT response curves, resulting in high-quality impedance tensors and tippers at all three sites. These impedance tensors were compared with data collected ~5 years ago at the similar locations by the Scripps Institution of Oceanography's OBEM (Chesley et al., 2021). The comparison reveals generally consistent curves in MT off-diagonal components, but considerable differences can be seen in the MT diagonal components. In addition, by reviewing the time series, we identified interesting occasional variations with frequencies around 1 Hz, likely caused by oscillation of water at depth. Moving forward, we plan to refine our time series processing to detect robust variations in MT responses, which are essential for identifying structural changes potentially driven by fluid migration associated with SSEs. Notably, a large SSE initiated within our monitoring area in November, 2024.

## AS25-0372

# Tectonic architecture of the Mitidja Basin (north-Central Algeria): magnetotelluric evidence and structural implications

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The Mitidja Basin is a significant active structure in northern Algeria, situated in a seismically active zone and having experienced several major earthquakes. Its strategic importance is further underscored by the presence of Algiers, the capital, making it a critical area for seismic risk assessment and urban planning. Additionally, the region holds hydrogeological significance, hosting the deeper Astian aquifer and the Quaternary alluvial aquifer.

The Mitidja Basin's crustal structures remain poorly understood due to limited geophysical data. This study fills this gap by investigating its geoelectric structures, using the magnetotelluric method. This technique utilises natural electromagnetic fields to image subsurface electrical conductivity. A survey was conducted along an 11 km NNE-SSW profile, with measurements taken at ten stations. Data processing yielded impedance tensors (Z) and the tipper (Tz) over a period range of $10^{-4}$ to $10^{3}$ seconds, depending on the total measurement time at each site. The dimensionality of the data and the distribution of regional conductive structures were analysed using the MT phase tensor, with the subsurface structure considered 2D and exhibiting an N80° E strike angle. The data were subsequently inverted using the MARE2DEM code. The resulting model has provided a detailed characterisation of the Sahel fold and the Mitidja Basin's tectonic architecture, revealing multiple fault structures, the most significant of which is a blind fault associated with the Sahel anticline. Additionally, the results have enabled an estimation of the basin's depth to the west and have helped clarify the divergence in the structural shape of the Sahel.

## AS25-0531

# Towards multi-source 3-D inversion of Swarm satellite data in terms of mantle electrical conductivity

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Time series of spherical harmonic coefficients of magnetospheric field, and its induced counterpart, obtained by analysis of observatory and satellite magnetic data, are sensitive to the electrical conductivity of the middle mantle, from the transition zone to the depths about 1200 km (Velímský & Knopp 2021). The corresponding regularized inversion scheme is formulated in the spherical harmonic formalism in the time domain, using the adjoint approach for efficient calculation of misfit gradient in the model space. On the other hand, the satellite-observed magnetic signals of ocean tides are sensitive to the electrical conductivity of the suboceanic upper mantle, down to the transition zone (Šachl et al. 2022, 2024). The forward and inverse modelling of the tidal problem shares some similarities with the magnetosphere-driven approach, such as spherical harmonic parametrization of the magnetic field, and use of the adjoint approach for evaluation of misfit sensitivities. However, due to harmonic characteristics of dominant tidal constituents, the problem is cast in the frequency domain. Also, focusing on the sub-oceanic upper mantle requires a spatially, rather than spectrally constrained model space of conductivity distribution, and different regularization techniques. In this contribution, we combine both methods to present a unified multi-source scheme for 3-D mantle conductivity inversion spanning the mantle depths from the surface, down to 1200 km.

## AS25-0645

# Assessment of the Kestanbol granite pluton in terms of enhanced geothermal system inferred from magnetotelluric imaging and thermal analyzes

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Granite plutons represent complex geological features that require a multidisciplinary approach encompassing thermal analysis, geochemistry and geophysics. The interplay of these disciplines ultimately improves our understanding of their structural geometry, formation and evolution and supports practical applications such as resource extraction. Granite plutons have proven to be important candidates for Enhanced Geothermal Systems (EGS) due to their high thermal properties and their ability to store heat. These systems are considered sustainable energy systems of the future, where energy is extracted from hot dry rock (HDR) in the Earth's crust. In this study, magnetotelluric data from fifty unevenly distributed measurement points were processed and three-dimensionally modelled to obtain a map of the Kestanbol granitic pluton in western Anatolia, Türkiye. Due to its high resistive physical resistivity properties, we could easily map the granitic pluton and distinguish it from contact metamorphism and faults, which are important for drilling for EGS. We also collected twenty-eight samples from the pluton and surrounding rocks of varying lithology, including volcanics and metamorphic rocks, to measure thermal conductivities and radiogenic heat production. We also used the thickness of the pluton from the magnetotelluric model and the U, Th, K concentration from the geochemical analysis to calculate the radiogenic heat flow. The results of the geophysical and geological analysis extend our knowledge of the Kestanbol granitic pluton for possible future EGS.

## AS25-0717

# A fast reduced basis modelling approach for geophysical electromagnetic methods

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With the fast development of machine learning methods, stochastic algorithms have become increasingly popular in electromagnetic (EM) inversions, as they allow for quantification of uncertainty, while being less sensitive to initial guess and local object function minimum. However, the computational cost of those approaches (e.g. Monte Carlo-style methods) using conventional discrete PDE solvers can be prohibitive, due to the "curse of dimensionality" from the high number of unknowns in the 2D or 3D frequency-domain EM problems. To address this issue, we compress the model space through model quantification and introduce a reduced basis method to rapidly solve the PDE problem arise from the finite-difference discretization of curl-curl equations. The reduced basis method aims to project the full solution space of a PDE problem to its lower dimensional subspace, with a series of transformation basis. The reduced solution space can therefore be rapidly calculated by the spanning of a series of basis functions from the orthonormalization of a number of full solutions. Comparisons between the new method against its conventional counterpart with synthetic and real-world tests shows a promising speed-up of up to 150x. This may provide a new tool to deal with challenges from near real-time simulations in industrial applications, or Bayesian inversions that require millions of forward calculations.

## AS25-0738

# Advanced application of audio and broad-band magnetotelluric techniques for sedimentary basin characterization and groundwater exploration in Adrar, southern Algeria

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Groundwater is a crucial resource in the Sahara, particularly in the Adrar region of Algeria, which relies on the Northern Sahara Aquifer System (SASS). However, the geological and hydrogeological characteristics of this system remain insufficiently understood. This study presents the first hydrogeophysical investigation in Adrar, combining audio-magnetotelluric (AMT) and broad-band magnetotelluric (BBMT) methods to explore subsurface geology. The area, located on the North African craton, has a complex history shaped by marine sedimentation, particularly in the Continental Intercalaire (CI) nappe. The water, mainly in Cretaceous formations, is essential for the Timimoun-In Salah axis' water supply. Data were collected at 14 AMT sites, spaced 200 meters apart, and 13 BBMT sites, approximately 10 km apart. The AMT data, collected along a 2 km east-west profile, offered high lateral resolution, while the BBMT data, with broader frequency coverage and deeper penetration, provided complementary information. The resistivity models generated from both techniques showed significant lateral and vertical heterogeneity, with resistivity values exceeding 1000 Ω.m, and areas of low resistivity indicating fluid pathways. Subsurface faults that facilitate groundwater infiltration from deeper sources were also identified. The BBMT data inversion revealed a highly resistive crust beneath the craton and a moderately resistive crust beneath the Saharan platform. This research advances the understanding of groundwater distribution and subsurface architecture, contributing to water security and sustainable development in the arid Adrar region, one of the hottest and driest areas on Earth.

**Keywords**

Groundwater; Adrar region; Northern Sahara Aquifer System (SASS); Hydrogeophysical investigation; Resistivity models

## AS25-0761

# Multichannel GPR Modelling and Application in Environmental Remediation

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The topic primarily aims to explore the opportunities inherent in the shallow-penetrating research method known as Ground Penetrating Radar (GPR), used in the frequency range of 10 MHz to 10 GHz. This non-invasive measurement method is widely applicable in the fields of archaeology, engineering geophysics, geotechnics, and shallow geological research due to its good horizontal and vertical resolution. Recently, due to advances in information technology and computing, the applicability of this method and the number of physical parameters that can be investigated using this method have expanded. Since the 2000s, multichannel devices allow the measurement of the electromagnetic wave propagation velocity in addition to the varying dielectric properties and conductivity of the subsurface medium.

The topic concerns the opportunities and limitations inherent in the mentioned geometrical arrangement using finite element modelling via gprMax library and subsequently explores practical feasibility, attempts to introduce geophysical inversion methods based on the amplitude, frequency, and phase properties (in spatial and vertical domains) of the signals returning from the medium. In terms of practical applicability, applying appropriate parameterization, possibilities may arise for classification of fluids in porous media and separation of fluids with different physical properties, thus enabling more precise and non-destructive delineation of certain environmental damages in i.e. the vicinity of damaged oil pipelines or landfills.

## AS25-0806

# Multi-resolution robust CSEM 3D Inversion for mineral exploration

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Controlled-source electromagnetic (CSEM) methods are indispensable tools in many geophysical applications, especially in mineral exploration. Compared to natural field EM methods, CSEM methods can be made immune to anthropogenic EM noise and, when implemented in the frequency domain, offer advantages for full 3D modeling and inversion. Despite recent developments, challenges related to 3D inversion remain.

We have extended the previously developed MR3DMod object-oriented 3D modeling framework in Python, with specific optimizations for performance and accuracy. This framework allows straightforward extension to include various geophysical techniques, including frequency domain EM, time domain EM, and potential fields on multi-resolution grids. The ultimate goal is to efficiently implement joint inversion and interpretation of various data types.

We present 3D inversion results for different source types in typical mineral exploration applications. We examine the resolution of inductive and galvanic dipole sources. A real data test example is also shown, where we compare the accuracy of the standard staggered grid and the multi-resolution approaches based on inverting various combination of electromagnetic field components (Ex, Ey, Hx, Hy, Hz). Additionally, to cope with possible data outliers or model inconsistencies, a robust norm of data residuals is implemented.

## AS25-0808

# A magnetotelluric investigation of deep crustal controls on the genesis and distribution of lithium-Bearing Pegmatites in the Borborema Province, Brazil

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The growing demand for strategic minerals like lithium and cobalt and rare earth elements, essential for the energy is driving new research on pegmatites. In Brazil, lithium-bearing pegmatites are explored using costly and environmentally impactful methods like borehole drilling. The Borborema Pegmatite Province (BPP) in northeastern Brazil contains over five thousand mapped pegmatite outcrops, yet their origins and depth extent remain poorly understood. Pegmatites in the BPP occur mainly in schists, quartzites, and granites/gneisses reworked during the Brasiliano orogeny (750–550 Ma). Dating indicates peak intrusion activity during this period. Modeling these pegmatites is challenging due to their thin structures and emplacement in host rocks with similar electrical resistivity, non-magnetic properties, and limited data. To address the issue of their origin, the magnetotelluric (MT) method was applied to model subsurface resistivity in southern BPP. Twenty-two MT stations, spaced 5 km apart and covering periods from 0.0001 to 1000 seconds, were deployed. Preliminary 3D resistivity models show high-resistivity structures (>10,000 ohm-m) in the upper 5 km, likely metamorphic rocks and granitoids of the Seridó Complex. Deeper, between five and 40 kilometers, a large structure with localized low-resistivity zones (<100 ohm-m) is found which may represent Ryacian intrusive rocks or magmatic underplating. These conductive structures are interpreted as potential sources of the pegmatites intruded in basement cover rocks reworked during the Brasiliano orogeny.

## AS25-0815

# Three-Dimensional Inversion of Magnetotelluric Data from Mt. Ruapehu, New Zealand

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The andesite–dacite stratovolcano Mt. Ruapehu formed ~230 ka ago at the southern termination of the Taupo Volcanic Zone (TVZ), a rifted arc and a centre of active rhyolitic volcanism. In the last century, Mt. Ruapehu has been frequently active with the last large phreatomagmatic eruption in 1995/96 and a steam driven eruption in 2007.

To image the magmatic system beneath Mt. Ruapehu, 40 magnetotelluric (MT) measurements were acquired in the area between 2007 and 2009. Previous 2-D and 3-D modelling of these data show the underlying electrical resistivity structure. However, due to the relatively sparse site distribution and the use of a finite difference 3-D inversion code that does not include topography, the resolution of existing models is coarse. To improve these resistivity models, in 2023, 28 new MT measurements were acquired at Mt. Ruapehu to fill gaps in the existing data, and achieve a uniform coverage of measurements around the volcano.

Here, we present preliminary results of the 3-D inverse modelling of the complete set of MT data acquired at Mt. Ruapehu using FEMALY: A Finite Element MAtlab LibrarY for Electromagnetics. Impedances were inverted for 18 periods between 3 ms and 341 s with particular emphasis on an appropriate representation of the rugged topography.

We will also compare our initial inversion findings from Mt. Ruapehu with the latest detailed models from the adjacent Mt. Tongariro.

## AS25-0817

# Observation of Electric Phenomena Associated with Eruptions of Strokkur Geyser, Iceland

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Strokkur Geyser, located in Haukadalur, Iceland, is one of the world's most active geysers, erupting every 5 to 10 minutes and reaching heights of up to 35 meters. Despite general understanding of its eruption mechanism—water heating, pressure buildup, and sudden release—many details remain unclear, including bubble formation dynamics, the role of dissolved gases, and interactions between water chemistry, temperature, pressure, and rock structures.

To investigate Strokkur's geothermal activity, we conducted a multi-EM time-lapse monitoring survey using DC resistivity, induced polarization, and time-domain electromagnetic methods. With repetition periods as short as 2 seconds, we achieved high temporal resolution of the eruption cycle. Experimental layouts were pre-designed using our electromagnetic finite element simulation and inversion library, FEMALY, and adapted in the field. Additional seismic, infrasound, and tilt meter recordings, along with video footage, provided supplementary data and precise eruption timestamps.

Preliminary results indicate that all electromagnetic methods captured clear evidence of the eruption process, showing consistent temporal variations in electric resistivity near Strokkur's conduit and pond. Even minor water level fluctuations were reflected in the EM responses, highlighting the sensitivity of the methods. However, the exact causes of these changes remain uncertain.

Future work will involve a full 3D inversion of the TEM data using FEMALY to determine the larger-scale electric conductivity structure. Further interpretation of the observed phenomena will contribute to a deeper understanding of Strokkur's hydrothermal dynamics in the context of existing theories.

## AS25-0869

# Noise reduction and upward continuation for shallow water magnetotelluric data

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Magnetotelluric data collected in shallow marine and lacustrine settings can be severely compromised by noise generated by wind-driven waves and tidal currents. This noise is mainly caused by instrument motion, and so is larger in the magnetometer sensors, which are highly sensitive to rotation in Earth's main magnetic field. Hybrid magnetotelluric responses can be computed by using low noise magnetometer data collected nearby on land, greatly reducing the noise. However, few two or three dimensional inversion codes are equipped to handle hybrid magnetotelluric data. Since the water column is one-dimensional, with water conductivity varying only with depth, one-dimensional theory can be used to convert hybrid responses to seafloor magnetotelluric responses. Although the magnetotelluric responses may exhibit two or three dimensional structure, the corrections for the water layers can be carried out on the individual components of the impedance matrix. Twelve sites of noisy magnetotelluric data collected at 20–40 m water depths in Spencer Gulf, South Australia, are shown to be greatly improved by this approach, particularly at periods between 2 and 10 seconds, where noise from ocean waves is largest. However, some three-dimensional magnetotelluric inversion codes are limited in their ability to handle bathymetry and seafloor responses. Then one-dimensional theory can also be used to propagate seafloor responses into sea (or lake) surface responses. We demonstrate this by computing lake surface magnetotelluric responses from 21 sites collected on the bottom of Mono Lake, California. Two dimensional inversions of lake bottom and lake surface are nearly identical, validating the methodology.

## AS25-0884

# Rotationally invariant transfer function for non-oriented VLF-EM systems

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Radio communication at very low frequencies (VLF, ~3 kHz to ~30 kHz) has been utilized by many of the world's major navies for nearly a century. At any given moment more than a dozen of powerful (up to ~1 MW) VLF stations placed around the world are transmitting narrow-band electromagnetic (EM) signals. These signals could be detected thousands of kilometers away from the transmitters, thus providing "free" remote sources for EM geophysical mapping.

The simplest and most robust modification of the VLF-EM method makes use of the total magnetic field amplitude calculated from the three orthogonal components of the magnetic field produced by a given VLF transmitter. The resulting maps clearly highlight conducting structures aligned with the direction to the transmitter. However, the structures striking in the perpendicular direction are barely visible or not imaged at all.

A natural solution is to use several different transmitters, which can produce various maps emphasizing linear features directed toward the respective transmitters. However, combining data from these maps into a single, clear image is challenging. To address this issue, we propose a rotationally invariant multi-transmitter VLF-EM parameter that can be derived using non-oriented EM receivers, thus retaining the main advantage of the total-field VLF-EM method. This approach allows for the creation of a unique, source-independent map, providing an objective representation of electrical conductivity structures.

## AS25-1186

# Sub-basalt imaging in Southeast Anatolian Orogenic Belt using magnetotelluric data

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Orogenic belts—fold-and-thrust zones—are closely associated with major hydrocarbon accumulations in terms of thermal maturity and reservoir conditions. However, when high-velocity rocks, such as volcanic formations, are present at or near the surface, conventional seismic exploration methods often fail to provide accurate structural imaging due to the dispersive nature of these rock types and the decrease in seismic velocity at the base of a thick cover layer. To overcome these limitations, the use of different geophysical datasets, such as magnetotellurics (MT), can offer a broader perspective on potential hydrocarbon-bearing zones. In this study, broadband MT data (0.0001–1000 s) were acquired from 63 sites in the Karacadağ Volcanic Complex and analyzed using three-dimensional modeling techniques to construct an electrical resistivity distribution associated with sub-basaltic sediments in the Southeast Anatolian thrust zone (Türkiye). The 3D resistivity model revealed a thick sequence of low-resistivity sedimentary layers sandwiched between a highly resistive basalt layer and a more resistive basement. A moderately resistive zone, which may indicate a potential hydrocarbon-bearing area, was also identified above a resistive basement.

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## AS25-1282

# Three-dimensional resistivity imaging of Pantelleria island: insights into its geothermal potential

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The island of Pantelleria, located in the Sicily Channel, is a volcanic system characterized by peralkaline (pantelleritic) magmatism and recurrent explosive eruptions that have produced prominent caldera structures. Active geothermal manifestations, including gas emissions, hot springs, and elevated temperatures detected in deep boreholes, underscore its potential as a geothermal resource.

To elucidate the island's subsurface and improve the understanding of its volcanic structures, geothermal reservoirs, and the hydrothermal fluid circulation pathways, an audiomagnetotelluric survey was carried, with 78 independent measurements. The resulting three-dimensional resistivity model delineates the geological and geothermal framework to a depth of 2.0 km below sea level.

The resistivity anomalies imaged by the 3D electrical model can be related to specific geological processes and physical conditions within the geothermal system, and accurately identify the main volcano-tectonic structures, particularly the La Vecchia and Cinque Denti caldera rims, which drive fluid circulation and storage within the hydrothermal system.

Comparison with available shallow and deep boreholes and geochemical emission areas provides further elements for interpreting our model to define the main hydrothermal source of the island.

This study highlights the fundamental role of caldera structures in influencing hydrothermal processes and improves our understanding of Pantelleria's geothermal potential. The results provide valuable insights for targeted exploration and sustainable exploitation of the island's geothermal resources.

## AS25-1299

# Electromagnetic Characterization of Geothermal Systems in Intracratonic Basins: Analysis of Unconventional Resources through Constrained Inversion

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Geothermal energy is a key renewable resource, offering a sustainable alternative for electricity generation with minimal environmental impact. Despite its global significance, Brazil's geothermal potential remains largely untapped, contributing less than 1% to the national energy matrix, according to the 2021 World Energy Resources report.

Recent studies have identified promising geothermal resources in Brazil, particularly in the crystalline basement of intracratonic basins such as São Francisco and Paraná. These basins may host both high- and low-enthalpy geothermal systems, including Hot Dry Rock (HDR) and Hot Wet Rock (HWR) reservoirs. However, most geothermal investigations in Brazil have been limited to depths shallower than 1 km, with deeper targets estimated through indirect thermal flux measurements.

Geothermal systems are typically associated with high heat flow, making them prime targets for conventional geothermal exploration. However, their electrical properties—governed by porosity, fluid content, salinity, and mineral alterations—can vary significantly. Electromagnetic methods, such as magnetotellurics (MT), offer a valuable alternative by mapping subsurface electrical conductivity variations and imaging deep geothermal reservoirs.

This study aims to integrate geothermal and magnetotelluric data to investigate geothermal systems at depths exceeding 1 km in Brazilian Intracratonic basins. By leveraging the deep exploration capability of MT, this research seeks to refine geothermal assessments and support the sustainable development of geothermal energy in Brazil.

## AS25-1327

# Adaptive Mesh Refinement in 3D Transient Electromagnetic Modeling Using Hanging Edges

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The transient electromagnetic method is a geophysical exploration technique used to investigate subsurface conductivity structures by means of controlled-source electromagnetic fields in the time domain. In the interpretation of field data, numerical modeling is a crucial tool driving inversion procedures and, moreover, allowing for the identification of suitable measurement configurations.

When planning field experiments, we carry out virtual electromagnetic experiments, i.e., we use synthetic models to replicate the test site in terms of geological, topographical and/or bathymetric settings and subsequently simulate the propagation of electromagnetic fields in these models. As an appropriate level of detailedness is required to obtain meaningful results, the construction of meshes tailored to each site and experimental configuration is an important but challenging task.

To allow user-guided mesh modification within the modeling routine, we propose a straightforward adaptive mesh refinement (AMR) technique. It extends the concept of hanging nodes to vector-valued finite elements used in electromagnetic modeling, thereby creating so-called hanging edges. By direct incorporation of mathematical constraints into the matrix system, this optional workflow component avoids time-consuming re-meshing using an external mesh generator.

Thus, the hanging edge technique serves a variety of applications, such as a-priori mesh refinement and AMR convergence studies. We demonstrate its application using a simple homogeneous half-space as an example.

## AS25-1351

# Processing of Magnetotelluric data in electromagnetically noisy environments

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Processing of Magnetotelluric (MT) data in electromagnetically noisy environments remains a challenging problem, especially in near infrastructure environment (like mining applications, geothermal studies) where coherent cultural noise may be ubiquitous and overwhelming. The standard processing toolkit now includes various robust methods, remote reference, and (to a lesser extent) multi-site methods. We are exploring novel ways to combine these, to better understand, characterize, and ultimately mitigate anthropogenic EM noise effects on broad-band and audio MT transfer functions. Typically, large data sets are acquired in this frequency range, often simultaneously at multiple sites. After spectral transformation of raw time series of electromagnetic field components, the frequency domain (FD) data may be represented as a 3D array, indexed by channel/site, time segment, and frequency, with the tradeoff between time and frequency resolution. High frequency resolution (long FFT windows) are preferable when noise sources are periodic (electric fences, AC trains, pumps, cathodic protection, etc.), and high time resolution (short FFT windows) when noise sources are intermittent. We are developing workflows that make use of multiple resolution levels, using various spectral transformation techniques. A major aspect of our work is to better incorporate principal components analysis (PCA) into routine workflows, e.g., by reducing dimension of the FD "data cube" along the channel axis. In the realm of more novel schemes, we are exploring application of multilinear-PCA. Throughout the work a range of robust statistical methods are applied. We further develop and refine MsDEMPCA software package optimized for performance and user experience.

## AS25-1384

# The Magnetotelluric Array Project and a High-Resolution Electrical Conductivity Model Compilation for the Contiguous United States

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In its 18-year lifetime, the United States Magnetotelluric Array (USMTArray) has acquired more than 1,700 long-period magnetotelluric (MT) stations covering the entirety of the contiguous United States. Funding from multiple federal agencies has sustained this effort to its completion in 2024. Important components of the project included active guidance and participation from the scientific community, the open and timely availability of all data, and the application of consistent instrumentation and robust data processing. Together with parallel advancement in the development of publicly available 3D inversion codes, the MT Array has revitalized the U.S. MT community and increased the visibility of MT within the Earth-science community. USMTArray data are used by researchers worldwide for fundamental and applied studies ranging from investigations of active and fossil tectonic margins to mineral systems assessment to estimating magnetic storm-induced geoelectric fields that interfere with electric power transmission. We review the history and development of the project, the challenges and successes in its execution, and lessons learned. We further present the up-to-date, high-resolution CONUS 3D electrical conductivity model compilation for the entirety of the contiguous United States, enabled by USMTArray, and highlight the breadth of research stemming from this rich data set.

## AS25-1418

# Comparison of the empirical GIC transfer functions at La Pobla de Massaluca station for two different geomagnetic events

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The empirical geomagnetically induced current transfer function (eGICtf) establishes a linear relationship between the GIC measured under powerlines and the magnetic field of a geomagnetic storm. This function depends on the characteristics of the powerline network and the electrical properties of the ground.

We analyzed the eGICtf at La Pobla de Massaluca (MAS) station under a powerline, considering two geomagnetic storms that occurred from May 10–12, 2024, and October 10–12, 2024. Our comparison showed differences suggesting that the powerline network characteristics were different on these two dates.

Additionally, we considered an elliptical representation of the complex vectors to examine the dependence of the GIC on the polarization of the geomagnetic field of the storm and to identify their potential effects on the GIC behavior.

## A35 Lithospheric studies and deep mantle conductivity

### AS25-0056

# Electrical conductivity of amphiboles at high temperature and pressure and its implication on Mid-Lithosphere Discontinuity

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Amphibole is thought to be the most abundant hydrous mineral in mantle xenoliths, which could be a potential contributor to mid-lithospheric discontinuities. Therefore, amphibole may induce the high-conductivity anomalies in the sub-continental lithosphere revealed by magnetotelluric (MT) data.

In this study, the composition of cratonic lithospheric mantle was simulated by synthesizing variable olivine and amphibole mixtures. The electrical conductivities of the mixtures were measured at high temperature and pressure 3.0 GPa. Using the data obtained in this study, the temperature for the breakdown of amphibole and the interaction between olivine and amphiboles was inferred. Based on our conductivity results and geothermal gradients and MT data, we found that amphibole may contribute to the MLDs in the global cratons.

## AS25-0087

# Inferring the Regional Deformation Mechanism of the Central Songpan-Ganze Terrane based on Magnetotelluric Array Data over the Northern Tibetan Plateau

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The central Songpan-Ganze terrane, located in the northern Tibetan Plateau, is bounded by the Qaidam Basin to the north, separated by the Kunlun fault, and the Qiangtang terrane to the south, delimited by the Jinsha suture. The region is characterized by numbers of left-lateral strike-slip faults, indicating distributed shear strain and eastward crustal migration. The dominant mechanism of crust-mantle deformation—whether driven by vertical asthenosphere upwelling or horizontal lateral extrusion—remains debated. To investigate, 192 broadband and long-period MT sites were analyzed using three-dimensional inversion with the LBFGS algorithm, deriving a reliable electrical structure model of the lithosphere. Key findings include: (1) Under the Ganze-Yushu sinistral strike-slip fault, there are a series of low-resistivity channels extending northward in the middle and lower crust, which correspond to the "finger" shaped low-resistivity intrusions under the Kunlun fault, indicating that these "finger" shaped conductors have already been developed within the Songpan-Ganze terrane, and may be related to large-scale sinistral strike-slip deformation in the region. (2) These channels exhibit weak lateral connectivity but significant vertical extent, highlighting the importance of vertical deformation mechanisms, likely influenced by mantle-derived thermal material upwelling. (3) The low-resistivity body in the Songpan-Ganze terrane narrows from west to east, with its eastern portion exhibiting an upward extension into the upper crust. This may indicate that the Songpan-Ganze terrane experienced heterogeneous stress during the process of accommodating tectonic deformation, the region was subjected to greater compressive stress, leading to upward thrusting and the formation of a high-angle thrust conductor.

## AS25-0247

# The study of the lithospheric magnetic field model based on MSS-1 and other Satellite Data

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We adopt the newest data of Macau Science Satellite-1 (MSS-1) and other satellites (Swarm and CHAMP) to create a global lithospheric magnetic field model by a sequential method. The satellite signals remain noises like the unmodeled external fields (ionospheric field, PEJ, and EEJ currents), orbital noise, tidal magnetic signal, and the noise between satellite tracks after removing the core field and large-scale magnetospheric field parts. In order to achieve the signals as pure as possible, we first remove real-time tidal signals and ocean current effects from the satellite data of quiet times. An along-track spherical harmonic high-pass filtering scheme filters the satellite orbital data, followed by singular spectrum analysis (SSA) in polar regions to mitigate the impact of prominent high-frequency anomalies. To further improve model accuracy, line leveling is applied to all pairs of adjacent measurements to reduce orbital track discrepancies. Finally, the Iteratively re-weighted least-squares (IRLS) method determines the spherical harmonic coefficients. The new model demonstrates excellent consistency with existing models such as MF7 and LCS-1. MSS-1 effectively captures small-scale magnetic field variations in mid- and low-latitude regions, providing a valuable supplement to the current satellite datasets. Moreover, the data processing approach significantly contributes to the refinement of lithospheric magnetic field models and offers promising applications in geophysical and geological research.

## AS25-0397

# Lithospheric electrical structure of the Iberian Peninsula

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This study presents a new three-dimensional (3D) electrical resistivity model of the lithosphere beneath the Iberian Peninsula, integrating magnetotelluric (MT) soundings collected over the past 30 years. Defining the lithosphere-asthenosphere boundary (LAB) remains challenging due to discrepancies among geophysical methods. The electrical lithosphere is characterized as a resistive layer overlying the more conductive asthenosphere. A total of 112 MT sites were inverted using the ModEM code, with an initial resistivity model based on regional geological constraints, including the EUcrust07 model and previous lithospheric studies. The model's mesh resolution was 11 × 11 km horizontally, with a LAB depth varying between 60 and 140 km. The inversion process refined the resistivity structure over 150 iterations, reducing the normalized RMS error from 40 to 2.1. The final model reveals significant lateral variations in lithospheric resistivity, particularly above 80 km depth, indicating strong heterogeneity. To define the electrical LAB (e-LAB), the steepest negative resistivity gradient method was applied, yielding depths between 78 and 110 km in stable regions, with a maximum depth of 138 km beneath the Pyrenees. These values align with previous MT studies but differ from seismic and gravity-based LAB estimates. The results underscore the complexity of lithospheric structure and highlight the importance of multi-method approaches in defining the LAB.

## AS25-0433

# Lithospheric magnetic field modeling based on MSS-1 and multi-satellite gradient data

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We develop a global lithospheric magnetic field model using spherical harmonic degrees up to 120. The new model is based on the combination of scalar and vector gradient data from the Macau Science Satellite-1 (MSS-1), CHAMP, and Swarm satellites. We removed external noise interferences such as ionospheric, tidal fields, and currents associated with the polar electrojet (PEJ) and equatorial electrojet (EEJ). The model was analyzed through power spectra, correlation coefficients, and sensitivity matrices. After comparing our results with previous models, we found that the incorporation of MSS-1 data indeed enhanced the correlation coefficients in the low-degree range and effectively reduced the decline in correlation at high degrees (greater than 60). MSS-1's low-inclination orbit design allows for capturing more magnetic field details in mid-to-low latitude regions, which significantly improves magnetic field modeling in these areas. We anticipate that future extensions of MSS-1's observation period and optimizations in data preprocessing will further enhance the model's spatial resolution and stability.

## AS25-0547

# Magnetotelluric monitoring of deep fluid flow during earthquakes and slow slip events in the subduction megathrust of northern Chile (19°–23° S)

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The largest earthquakes occur at tectonic plate boundaries in subduction zones, known as subduction megathrusts. The subduction megathrust in northern Chile (19°–23° S) has been monitored since 2007 by the Integrated Plate Boundary Observatory Chile (IPOC) network, which includes an array of 11 long-period magnetotelluric (MT) sites to infer changes in deep fluid distribution. Here we present results from the interval encompassing the precursory and foreshock seismic sequences of the 2007 Mw 7.7 Tocopilla and 2014 Mw 8.1 Iquique earthquakes, an interval that also includes a dozen slow slip events. Analysis of the MT data revealed that fluctuations in external magnetic fields (source effects) superimpose on the temporal variations of the MT parameters. After minimizing the influence of these sources, we identified a significant anomaly in the MT monitoring data from mid-2012 to early-2014 at a site located above an unbroken megathrust segment. The anomaly can be explained by a decrease in resistivity within a seismically active fault within the upper plate that appears to be associated with the megathrust. However, no clear and robust anomalies were detected at sites closer to the megathrust segments ruptured by the 2007 Tocopilla and 2014 Iquique earthquakes. We discuss the monitoring capabilities of the IPOC MT array in general and show a possible fluid flow event within the megathrust region that would have gone undetected.

## AS25-0750

# Regionality of mantle conductivity inferred from combining a physics-based model and observatory data of geomagnetic daily variation

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This study analyzes geomagnetic data of daily variation at 71 stations, detecting the global distribution of electrical conductivity in the mantle. It is necessary to consider the Sq field in the daily variation analysis because the geomagnetic distribution is complex and rejects the plain wave assumption, unlike conventional magnetotellurics. However, 71 stations are still insufficient to draw an Sq field with high spatial resolution. Instead, the GAIA model (Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy) is used as the inducing field. The GAIA assimilates the meteorological reanalysis data, JRA-55, into the whole atmosphere-ionosphere coupled model, making it a well-modeled Sq field.

First, we executed spherical harmonic expansion of the magnetic field of the GAIA for a three-day time series, corresponding to three consecutive solar quiet days. Next, 3-D forward modeling in the spherical coordinate was executed in the frequency domain. We suppose a 1-D structure in the Earth under the ocean-land lateral contrast. Several 1-D models were tried, and we searched for the best-fitted model for each station. The results indicate that beneath Europe, the conductive model, in which electrical conductivity exceeds 0.1 S/m in the upper mantle, is preferred. Conversely, the upper mantle beneath the northwestern Pacific is considered resistant, with conductivity of 0.01 S/m or less. This difference may be attributed to the water content carried by a subducting slab, as the maximum amount of water can be controlled by the slab's temperature.

## AS25-0772

# Structure and Tectonics of the São Francisco Craton–Ribeira Orogen Transition and Cabo Frio Terrane: A Multigeophysical Analysis in Southeast Brazil

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This study investigates the complex tectonic framework of southeastern Brazil, focusing on the transition between the São Francisco Craton, the Ribeira Orogen, and the Cabo Frio Exotic Terrane. By integrating regional magnetotelluric (MT) data with other geophysical datasets, the research aims to unravel the deep lithospheric structure and tectonic processes associated with continental orogenic belts and their relationship with the Campos Basin, a key petroleum province. A total of 100 long-period MT stations were deployed across a 500 km by 400 km area, arranged along five NW-SE profiles. Using the ModEM-ON package, a 3D resistivity model MT was constructed and integrated with gravity, seismic tomography, and geothermal data. Key findings include conductive anomalies beneath the São Francisco Craton, correlated with positive P-wave velocity anomalies and normal thermal flux, suggesting crustal rejuvenation processes. Well-defined suture zones were also identified in both the geoelectric model and seismic tomography of the Ribeira Orogen, highlighting subduction and collision events during the Neoproterozoic. Furthermore, distinct suture zones delineate the boundaries between different tectonic blocks within this orogenic belt. The presence of anomalous conductors at the interface between the Ribeira Orogen and the Cabo Frio Terrane reinforces the interpretation of an accretionary process during the Cambrian, in which the Cabo Frio Terrane was amalgamated with the Ribeira Orogen. These results challenge previous models that suggested an intracontinental evolution for southeastern Brazil, providing compelling evidence for the significance of Neoproterozoic-Cambrian accretionary processes, including ocean closure and continental block collisions.

## AS25-0868

# Magnetic sounding of the deep Earth: response of the fluid core

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The electrical conductivity profile of the deep mantle remains a topic of interest for various research fields such as mineralogy, seismology, etc. One of the investigation methods is to consider temporal variations in the external magnetic field, i.e., coming from currents inside the ionosphere and magnetosphere, to then relate them to changes of the internal magnetic field inside the mantle. These studies then aim to invert for the mantle's electrical conductivity profile while treating the core as a solid conductor. This is certainly a valid approximation for signals with periods smaller than the mantle electromagnetic time scale, yet this work aims to account for the fluid nature of the core. This may be important for inducing fields with long periods, such as signals in sync with the 11 year solar cycle, for which the induced field may be mistaken as a field emanating from the core dynamo. Multiple linear hydromagnetic simulations are run using the XSHELLS code in spherical geometry. Different configurations are being tested, both for the background field inside the core as well as for the inducing field. The parameter space is mapped by adjusting magnetic diffusivity, rotation rate and kinematic viscosity. The simulations provide the fluid response at the core-mantle boundary which can then be directly compared to the analytical response for a solid core. Insights on the difference in amplitude, phase shift as well as the possible increase in complexity between both responses could then be used to further constrain the mantle induction studies from above.

## AS25-1024

# Magnetotelluric characterisation of subsurface structures across different geological settings

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Imaging conductive zones associated with rock alteration and mineralized fluid-filled pores is a critical challenge in applied geophysics. The magnetotelluric (MT) method has proven to be an effective tool for mapping conductive structures and delineating geothermal reservoirs, as it is sensitive to electrical charges at conductive boundaries and assures a great depth of investigation. The comprehension of the electrical rock properties is essential to decode the dynamics of a geothermal system, providing key insights for its sustainable resource exploitation.

The Chaves Graben, located in northeast Portugal, is the most significant low-enthalpy geothermal field on the mainland. In the 90s, Audiomagnetotelluric (AMT) and Vertical Electrical Sounding (VES) studies revealed conductive structures at depth in the vicinity of the Chaves-Verín depression and the N70–80 W fault, suggesting potential areas of hydrothermal circulation, which is consistent with the known thermal manifestations.

To further investigate the region, additional MT data were collected, with Broadband Magnetotelluric (BBMT) instruments with a record time of ~8 hours, in campaigns between 2011 and 2012, extending the survey area further north. This study analyses this data set of 68 MT soundings, distributed across four ~10 km-long E-W transects, to refine our understanding of the Chaves Basin, its structural framework, and potential interaction with the geothermal reservoir. Preliminary results from a 3-D inversion will provide fresh insights into subsurface conductivity, offering improved constraints on the geothermal system.

This work is supported by the Portuguese Fundação para a Ciência e Tecnologia, FCT, I.P./MCTES through national funds (PIDDAC): UID/50019/2025 and LA/P/0068/2020 (https://doi.org/10.54499/LA/P/0068/2020).

## AS25-1094

# Electrical conductivity model of the Australian continent

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We present an Australia-wide 3-D electrical conductivity model that extends from the surface to the asthenosphere. The model was obtained by inverting the magnetotelluric responses from AusLAMP array and the legacy geomagnetic field responses. In order to invert this large data set, we applied a distributed 3-D electromagnetic inverse solver GoFEM that performs the 3-D inversion of plane-wave MT transfer functions in the spherical frame and supports multi-scale and locally refined meshes, thereby allowing us to accurately model 3-D electromagnetic induction effects across the broad range of scales over the continent. Thanks to these methodological advances, we are able to image the coherent crustal and lithospheric conductivity anomalies, which exhibit correlations with major tectonic units, and unlock new insights into the crust-mantle controls on the occurence of major mineral resources.

## AS25-1095

# The lithospheric structure beneath Britain from a 3D electrical resistivity model

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The complex geological history of Britain has been investigated using various geological and geophysical approaches since before the beginning of modern science. However, its deep lithospheric structure remains enigmatic. Magnetotelluric (MT) data provide key insights into the electrical resistivity structure of the lithosphere, offering valuable constraints on geological processes and tectonic evolution. Here, we present the first fully three-dimensional (3D) electrical resistivity model of Britain (BERM-2024), derived from the inversion of long-period MT data. The model, which images the resistivity distribution from approximately 5 km to 200 km depth, demonstrates good agreement with known geological structures while also revealing previously unidentified features.

At crustal depths, shallow conductive anomalies correlate with sedimentary basins along the west coast of Britain, such as the Cheshire Basin and the Welsh Massif, whereas resistive anomalies correspond to granitic plutons in the Scottish Highlands and Cornwall. A strong resistivity contrast delineates the Southern Uplands Fault, marking the boundary between two tectonostratigraphic terranes in Scotland. At depths of ~95–200 km, we identify a prominent NW-SE oriented conductive anomaly beneath the West Midlands region. To our knowledge, this feature has not been previously reported in other geophysical studies.

The integration of multiple geophysical datasets is essential for refining our understanding of lithospheric composition and processes. Here, we discuss how joint inversion of MT with seismic and gravity data can enhance the imaging of structures and provide new insights into the nature of previously unknown lithospheric features.

## AS25-1197

# Imaging, characterizing and monitoring volcanic plumbing systems of Mayotte and Montagne Pelee by combining experimental petrophysics and land/marine magnetotellurics

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Since 10 May 2018, Mayotte is experiencing one of the largest offshore seismovolcanic crisis of the 3 last centuries. The MAYOBS1 scientific mission (2–19 May 2019, Marion Dufresnes boat) discovered a 820 m-high new volcanic edifice (named Fani Maore), with an estimated volume superior to 6.55 km3. Between 2018 and 2021, geophysical monitoring revealed a global eastward displacement of 21–25 cm combined to a 10 to 19 cm subsidence of Mayotte, and numerous earthquakes (> 100,000) at unusual depth (22 to 45 km). A combination of broadband land and marine MT surveys allowed to obtain a 30 km deep 3D resistivity model of the island, unveiling two major conductive bodies at 22 and 12 km depth, with one interpreted as a volcanic mush. A new methodology, combining high pressure conductivity-temperature measurements and sensitivity study on the 3D model, achieved an estimation of the partial melt content of the mush between 25% and 40%. In addition 3 permanent MT stations are monitoring the plumbing system. On the other side of the earth, Montagne Pelee volcano (Martinique, west indies) is experiencing since 2019 a less spectacular seismic awakening with volcano tectonic events below 10 km depth and a more superficial activity in the first kilometers. In 2023 a high quality broadband MT survey allowed to obtain a 3D conductivity model of the volcano down to 20 kilometers. An off centered 11–13 km depth conductive body appears to be a good candidate for a volcanic mush and will be discussed.

## AS25-1229

# Multi-scale imaging of 3-D electrical conductivity structure under the contiguous US

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The completion of the first-of-its-kind continental wide magnetotelluric (MT) array over the conterminous US, referred to as USArray, has opened new opportunities for imaging 3-D electrical conductivity under continents with unprecedented coverage. In this contribution, we present a new 3-D electrical conductivity model of the contiguous United States obated from the inversion of 1600 USArray stations covering the entire contiguous United States on a quasi-regular 70-km grid. The use of a novel multi-scale 3-D imaging approach based on locally refined model grids allows us to consistently incorporate a large range of spatial scales and image 3-D electrical conductivity distribution from the upper crust down to the astenospheric mantle. This 3-D conductivity model unravels the complex tapestry of the continent geology and tectonics and provides an unprecedented opportunity to explore correlations between electrical conductivity variations and the location of critical mineral deposits as well as quantify the 3-D geomagnetically induced fields taking into account realistic 3-D subsurface electrical conductivity variations.

## AS25-1274

# Magnetotelluric constraints on lithospheric structure beneath the Albertine-Rhino Graben, Uganda: initial results of the DRIAR project

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Continental rifting is a critical component of the plate tectonics paradigm. While continental rifting is typically accompanied by magmatism, some rifts are magma-poor. The NSF funded DRIAR project focuses on advancing our understanding of the processes associated with magma-poor (dry) rifting by studying the Albertine-Rhino Graben, Uganda: the northern part of the Western Branch of the East African Rift System. DRIAR is using a combination of geophysical, geological, geochemical, and geodynamic techniques to test 3 hypotheses: (1) in magma-rich rifts, strain is accommodated through lithospheric weakening from melt, (2) in magma-poor rifts, melt is present but yet to breach the surface which weakens the lithosphere such that strain is accommodated by upper crustal extension, and (3) in magma-poor rifts, there is no melt at depth and strain is accommodated along pre-existing structural weaknesses such as inherited compositional, structural, and rheological lithospheric heterogeneities. Here, we provide an overview of the project, with an emphasis on magnetotelluric (MT) results.

Data from 56 MT stations collected in the Albertine-Rhino grabens have been modeled using ModEM and Jif3D inversion algorithms. Models from both inversion routines show a series of conductors in the lower crust and upper mantle that are suggestive of the presence of partial melt, although other explanations for lower crustal conductors are possible. Curiously, the strike of these conductors appears to be nearly perpendicular to that of the rift system. We will present models and an initial interpretation, as well as early results from other methods deployed during DRIAR.

# IASPEI Symposia

## S01 Observational Seismology – Open Session

### AS25-0019

# Evidence for the Trench Outer Arc Movement: Slip Distribution of the May 12, 2019, Mw 6.1 Costa Rica–Panama Earthquake

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We investigated the slip distribution of the 2019 Mw 6.1 earthquake that occurred at the Costa Rica–Panama border on May 12, 2019, 19:24:50 (UTC). Our research associated this earthquake with the north-trending strike-slip Canoas fault within the Panama Microplate (PMP). Finite fault slip was obtained using eight near-field seismic data, a local 1D velocity model by Quintero and Kissling (2001), the moment tensor nodal plane (strike=186º, dip=87º, rake=-177º) with a seismic moment release of 1.53e+18 N-m, and a hypocenter at 8.5240º N latitude, 82.863º W longitude, and a depth of 30 km. The rupture evolution indicates a small slip at the hypocenter and surface at the initial rupturing time. Two to three seconds later, the slip was higher and located 5 km up-dip from the hypocenter, moving up to the surface with a width of 10 km and a slip of about 0.08 m. Subsequently, it extended along the strike another 20 km with a width of 10 km, reaching a maximum slip 5 to 7 seconds after the calculated origin time with slip values ranging from 0.08 to 0.12 m. Our results indicate that the earthquake was caused by a dextral southward-striking strike-slip fault on the upper PMP (Canoas fault), and the fault slip model exhibits a thick 90º rotated L-shaped pattern covering a total length of 30 km, with most of the slip concentrated at the surface and a maximum slip of 0.12 m.

## AS25-0027

# Seasonal seismic patterns: a statistical exploration

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Does seismic activity vary with the seasons? The tropical year provides a natural framework for investigating potential seasonal variations in seismic rates. This analysis employed the non-parametric Kuiper's test (Kuiper, 1960), an extension of the Kolmogorov–Smirnov statistical test, specifically designed for circular data. The approach builds on methodologies previously applied to studies exploring the influence of solar and lunar cycles on global earthquake distributions (Kossobokov and Panza, 2020) and variations in seismic activity during spring tide cycles (Nekrasova et al., 2024).

We analysed comprehensive time-space-magnitude datasets from regional earthquake catalogues, including the North Tien-Shan region catalogue (SEME), the Lake Baikal catalogue (BDGS), the eastern Alps catalogue (Rebez et al., 2024), and the Nevada catalogue (Trugman, 2024).

This study highlights the importance of statistical methods in uncovering hidden patterns in seismic data and contributes to a deeper understanding of the factors influencing seismic activity.

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## AS25-0035

# Seismicity, reflector, and crustal fluid in Iwaki region, northeastern Japan

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The Tohoku-Oki earthquake with M 9 occurred on March 11, 2011. Many remarkable changes in crustal activity were observed in Japan after the earthquake. The Iwaki area in northeastern Japan is one of the areas where seismic activity increased drastically. The high seismic activity area is located in a triangle with one side length of about 50 km. The two seismic boundaries at depths of around 30 km and 15–23 km were detected just beneath the high seismic activity area (Usuda et al., 2022). The two boundaries were identified as Moho and mid-crustal boundaries. It was suggested that the mid-crustal boundary was related to crustal fluid. In the subduction zone, the dehydration from the descending slab is expected. The synthetic simulation was done to know the dehydration from the slab. The large dehydration at the depths of about 30 km – 70 km was suggested by the results of the numerical simulation. The seismicity data of the Japan Meteorological Agency indicated the existence of a high seismic activity zone in the area. The high seismic activity zone connected the Iwaki area and subducting oceanic plate. The contact point at the slab was the depth where the large dehydration was expected based on the numerical simulation. The high seismic activity zone could be a channel of the fluid from the slab to the Iwaki area. It is suggested that the seismicity change in the Iwaki area is related to the dehydration from the slab.

## AS25-0104

# A Spatial Forecast of Some Mw≥6.5 Earthquakes in California and Nevada

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A previously published study (Ebel and Chambers, GJI, 2016) showed that the M≥4 seismicity prior to several large California earthquakes occurred randomly along the future fault ruptures and at rates exceeding 0.5 M≥4 events peryear. Building on this observation, this paper presents a prospective forecast of the locations of the next Mw≥6.5 earthquakes in California and Nevada based on the locations and rates of occurrence of M≥4.0 earthquakes during the past 30 years, called here preshocks. The time period of the forecast is arbitrarily set at 33 years. The forecast faults are the Anza section of the San Jacinto Fault, the Calaveras Fault, the creeping section of the San Andreas Fault, the Maacama Fault, the San Bernardino section of the San Jacinto Fault, and the southern San Andreas Fault, all strike-slip faults in California, and the normal-faulting Wassuk Range Fault in Nevada. The temporal history of preshocks for past M≥6.5 earthquakes in California do not indicate when the future mainshock will occur. The probability of just one of the forecast events actually taking place during the forecast time period is less than 2%. Outside of California, preshock activity was observed before the 2016 Mw7.0 Kumamoto, Japan earthquake, the 2023 Mw 7.8 Kahramanmaras, Turkey earthquake, and the 2017 Mw 6.5 Juizhaigou, China earthquake, all strike-slip events, as well as the 2008 Mw 7.9 Wenchuan, China thrust earthquake, although the two mainshocks in China had preshock rates less than 0.5 events per year.

## AS25-0111

# A method for estimating the seismic data and application in China National Seismographic Network

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The reliable deep structure of the crust and uppermost mantle is an important source of information for understanding the seismotectonics. High quality seismic data is the foundation for obtaining reliable deep structures. However, some studies show that the instrument response of broadband seismometer varies over time, which is different from the manufacturer's nominal value. Therefore, it is necessary to estimate the quality of seismic observation data before carrying out the deep structure research. Based on analyzing the characteristics of the seismic data from China National Seismographic Network in the past 10 years, we developed a method for estimating the seismic data, and evaluated the quality of seismic observation of these stations. We found that about 5% of the China National Seismographic stations exhibit variations in instrument response over time. The deep structure obtained from these station data revealed significant differences in different period, even by using the same data processing flow and method.

## AS25-0153

# Crustal thickness and compositions in the South China Block constrained from receiver functions and the autocorrelation of teleseismic body wave

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The South China Block has experienced long-term and multi-phase tectonic movements and extremely complex evolution. Investigating the crustal structure and composition is crucial for understanding the formation and evolution in this region. Crustal thickness, average P-wave velocity and Vp/Vs ratios are estimated using the H-κ-Vp stacking of teleseismic receiver functions and P-wave autocorrelations recorded for 284 permanent stations belong the China digital seismic network. Our results show that the crustal thickness in South China ranges from 25.6 to 61.8 km, with an overall trend of being thicker in the west and thinner in the east. Yangtze Craton shows significant variations in crustal thickness (30–50 km) and velocity ratio (1.63–1.95). The average crustal thickness, Vp/Vs ratios, and P-wave velocity of Sichuan Basin are 43 km, 1.78, and 6.33 km/s, respectively. These observations are generally consistent with global shield/cratons. The average crustal thickness and P-wave velocity in Songpan-Ganze block are 52.5 km and 6.22 km/s, respectively. Some stations in this area have Vp/Vs ratios greater than 1.9, which may be related to partial melting in the crust. The Cathaysia Block has a thinner crust (30.2 km) and lower Vp/Vs ratio(<1.70), indicative of a felsic crust caused by the delamination of mafic lower crust. The coastal regions of Fujian and Zhejiang have relatively higher average crustal Vp/Vs ratios (1.75–1.86), which are likely related to Cenozoic basaltic magmatic activity in the area. Panxi region has a thicker crust (50 km) and a relatively high crustal Vp/Vs ratio, which may be associated with magmatic underplating.

## AS25-0156

# Study on unified model of subsurface faults and velocity structure in Korean Peninsula

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The Republic of Korea recognized the need for systematic research on subsurface faults after experiencing the 2016 Gyeongju earthquake (M 5.8) and the 2017 Pohang earthquake. Both earthquakes occurred on underground faults not visible on the surface, making it difficult to determine the causes of the seismic events. Additionally, the Pohang earthquake, triggered by drilling and water injection for geothermal power generation, had a shallow hypocenter, which made accurate hypocenter determination challenging. This highlighted the necessity for developing a 3D seismic velocity structure for accurate of the absolute hypocenter location.The Korea Meteorological Administration is developing a unified model of the three-dimensional subsurface fault and velocity structure of the Korean Peninsula to determine the causes of earthquakes and improve the accuracy of earthquake information. During the first phase (2018–2021), the project focused on the Seoul metropolitan and Yeongnam regions, which led to the development of an initial unified model of the three-dimensional subsurface fault and velocity structure. The second phase (2022–2026) is currently being conducted, targeting the Gangwon region, and the third phase (2027–2036) will conduct integrated surveys of the Chungcheong, Jeolla, Jeju regions, and surrounding seas. In addition, we are conducting various studies to utilize and apply this initial model. In this study, we introduce the development and application of the unified model of subsurface faults and seismic velocity structure in the Korean Peninsula.

## AS25-0195

# Monochromatically low frequency marsquake and its moment tensor and source time function

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From 2019 to 2022, InSight observed over 1300 marsquakes. We discovered that a marsquake exhibits a distinctively monochromatic feature dominated by low frequencies. The spectra of the P and S waves show a peak around 0.2 Hz, lacking energy above 0.5 Hz. The characteristics are not observed in the other events. Based on the characteristics, we concluded that the monochromatic peak is likely caused by the source. To investigate the marsquake further, we estimate the moment tensor and source time function by performing waveform inversion. Whereas the source time function of a single pulse cannot explain the waveform, the waveform fitting improves significantly by convolving the source time function with a duration of 10–15 s that was determined from the observed waveforms. The obtained source time function is oscillatory. The residuals between observed and synthetic waveforms were minimized by a shallow source near the surface, and a deep source around 60 km depth. Whereas the shallow source can fit direct P and S waves well, it fails to model subsequently arriving waves. In contrast, the deep source can model the subsequently arriving waves as well as the direct waves. Although we cannot completely reject the shallow source, the deep source appears more consistent with the observations. The deep marsquake may occur, for example, similarly to deep low frequency earthquakes below the Moho with which fluids are likely involved.

## AS25-0209

# Relocation of the seismicity of Oman

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We combined the International Seismological Centre bulletin with the Oman National Bulletin produced by the Earthquake Monitoring Center, Sultan Qaboos University. The resulting comprehensive bulletin contains 2,994 events with local, regional and teleseismic phases within our area of interest between 2014–2024. We first relocated the bulletin with iLoc, a single-event location algorithm that takes into account potential correlated travel time errors and uses the global 3D RSTT crust and upper mantle velocity model. Before applying the second step of our location procedures, we performed further quality control on the iLoc results by removing events recorded by less than 3 stations or 4 arrival times. We then relocated the events with Bayesloc, a non-linear Markov Chain Monte Carlo multiple event location algorithm, using the reviewed iLoc locations as input and setting tight a priori constraints for suspected explosions. Bayesloc was run with 10 Markov chain for 80,000 iterations. Our results show significant improvements in the view of seismicity. Using confirmed quarry blasts, we demonstrate that our method can facilitate identifying anthropogenic events that form the majority of onshore events in the region.

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## AS25-0213

# Statistical analysis of earthquake distribution in Bulgaria—update of seismogenic zones

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The study of the space—temporal distribution of earthquakes is of fundamental importance for understanding the physics of the earthquake generation process. The results of the earthquake distribution can be interpreted as confirmation of the concept that the grouping of them is an essential aspect of seismicity, which provides key information about the dynamics and contemporary tectonic development of our planet.

The seismicity of the Balkans (including Bulgaria) is unevenly distributed in space, which gives grounds for grouping earthquakes into geographically defined zones, called seismogenic zones. The seismotectonic analysis of the Central Balkans shows that modeling seismicity through seismogenic zones is more appropriate for the region than modeling through linear or three-dimensional fault structures.

The space distribution of seismicity in Bulgaria is uneven, which gives reason to group earthquakes generated on its territory with several main seismogenic zones, defined in numerous studies. Each of these zones is characterized by its specificity in seismotectonic, geological and geophysical aspects. Analysis of seismicity in different seismogenic zones is an integral part of compiling earthquake catalogs and is essential for defining seismic sources in a specific seismogenic zone.

The study presents the seismicity in the seismogenic zones defined on the territory of Bulgaria for historical and contemporary periods and analyzes of the space-temporal distribution pattern of earthquakes in them.

## AS25-0281

# Tomographic Image of NE India and its Surroundings Using Surface Wave Data and its Tectonic Implications

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Crust and upper mantle tomographic images of NE India and its surroundings were obtained by inversion of Rayleigh wave data recorded at regional distances. Bengal Basin comprises a thick layer of sediments; thickness increases slowly from west to east with a sudden increase across the Eocene Hinge zone. Indo-Gangetic Plains and Brahmaputra River valley comprise ~5–6 km thick sediments. Crustal thickness in the higher Himalayas and southern Tibet is ~70 km. Its value varies between ~30 km to ~40 km in the rest of the study area. The lithosphere below the Shillong plateau and Mikir hills bend upwards. We propose that this region represents the crest of the buckled-up Indian plate. Patches of low-velocity medium are present in the lower crust of southern Tibet below various rift zones indicating the presence of either partially molten material or aqueous fluid. Moho depth changes from ~75 km to the west of the Yadong Gulu rift zone to ~60 km to its east indicating the complicated effect of underthrusting of the Indian plate below the Eurasian plate. The tomographic image of the same region for S wave velocity obtained using Love wave data is similar. However, there are some differences in the depth of the sedimentary basin in the Bangladesh region, indicating the possible presence of anisotropy in the sedimentary layers. The beginning of the break-up between the northern and the southern parts of the Indian lithosphere is observed below the Eastern Himalayas from Love wave tomography but not from Rayleigh wave tomography.

## AS25-0283

# On one approach to monitoring the process of earthquake occurrence

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The processes, associated with the occurrence of earthquakes, cover two stages: slow (can last for decades) and fast (Foreshock, Earthquake, Aftershock). By authors was showed that these processes can be studied based on solutions of the corresponding quasistatic and dynamic 3D problems of Elasticity theory. Already in the 20$^{th}$ century, seismologists discovered that before an earthquake, in the zone of the expected earthquake, there is a significant deformation (movement of points) of the surface of the lithospheric plate or block of the Earth's crust. Simultaneously, in the specified area the huge amount of deformation energy accumulates (W). Reaching by this energy the critical value leads to the occurrence of earthquake of the corresponding magnitude (M).

By the authors were found solutions to the corresponding quasistatic and dynamic problems of elasticity theory for the layered package of isotropic plates, when the values of the displacements of the points of the contact surface between the first and second layers are known, as the result of measurements of inclinometers and deformographs placed there. Having the values of the stress tensor components, according to the well-known formula of Elasticity theory is determined the deformation energy. The approach allows to trace the change in energy over time based on regularly conducted new measurements. The automated computing program has been developed, which makes it possible to trace the entire process of earthquake occurrence in seismically dangerous regions of the Earth.

## AS25-0319

# On the current enhancement phase of the ISC-GEM Global Instrumental Earthquake Catalogue

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Since its first release in January 2013 (Storchak *et al*., 2013), the ISC-GEM Global Instrumental Earthquake Catalogue (www.isc.ac.uk/iscgem/index.php) became one of the most used datasets in seismological as well as broad geoscience research (for context, we tracked about 400 works since 2017 that used the ISC-GEM Catalogue). The catalogue is updated annually and with each new release we improve and expand the catalogue by adding earthquakes in different time periods and refining existing solutions (e.g., Di Giacomo *et al*., 2018; Di Giacomo and Storchak, 2022). As for any earthquake catalogue, however, there is always room for improvements. We have recently identified further tasks that will enhance the catalogue both in completeness and accuracy of the source parameters listed. Hence, in this contribution we report on the latest and planned developments of the catalogue, which include pre-1964 earthquake location (and corresponding uncertainty) reassessments following the location algorithm update discussed in Di Giacomo *et al.* (2025); MS improvements following the digitization of bulletins from the personal collection of the late W.H.K. Lee as well as other targeted tasks that will improve the catalogue in different time periods.

## AS25-0371

# Design and performances of 6-component optical borehole strainmeter

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Due to their high resolution and near real time capabilities, borehole strainmeters are a critical complement of satellite-based geodetic systems (GPS/GNSS) and satellite interferometry. However, commercial strainmeters remain expensive and usually provide only the 3 horizontal components of the strain tensor. We propose a novel design able to detect the 6 components of the 3D strain tensor at relatively low cost. Here, we embed 6 compliant elastic gauges in a sphere in order to evenly sample space directions. Each gauge exhibits an amplification ratio of ~30. Interrogated by Fabry-Perot interferometers illuminated by a single laser diode through a multichannel fiber cable, these opto-mechanical systems provide a strainmeter resolution < 1 nanostrain (DC-500 Hz). A supplementary interferometric device is also implemented to detect and correct non-geometrical optical phase changes due to pressure and temperature variations. An original building method allowed us to mold composite body around a thin sphere equipped by the optical strain gauges. An adjustable pressure device is integrated to allow *in situ* calibration in order to correct the 3D strain tensor from borehole and cement heterogeneities. This cost-effective strainmeter has been successfully installed in November 2023 in a 30 m deep borehole at the Larzac Observatory in the French Massif Central. We present here the instrument capabilities to display 3D geophysical strain (tides, earthquakes) and hydrological signal due to aquifer water motion.

## AS25-0414

# Landslide Records in Türkiye: Seismic and Remote Sensing Insights

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On February 13, 2024 (~11:30:10 UTC), a massive landslide (~1.2 $Mm^3$) occurred at the Çöpler Gold Mine in Erzincan, Türkiye, trapping nine miners under the heap leach pad and causing tragic deaths. This landslide was recorded at seismic stations up to 400 km away. Long-period signals separated by 48 seconds indicated two distinct pulses corresponding to two sources, reflecting the complex dynamics of the landslide, supported by optical imagery. These pulse wave trains were analyzed using a single-force model with Bayesian bootstrap-based probabilistic inversion. Joint analysis of remote sensing data, field observations, and source inversion revealed bilateral propagation: (1) west-northwest (WNW) and (2) north-northeast (NNE), respectively. Continuous slow deformation over four years, with average rates of up to 60 mm/yr, was identified using the Interferometric Synthetic Aperture Radar (InSAR) technique. Strikingly, the cyanide leach pond showed 85 mm/yr significant deformation.

The Çöllolar coalfield Afşin-Elbistan B Thermal Power Plant landslides in February 2011, which involved two catastrophic collapses within a week, resulted in 11 fatalities and displaced over 50 million tons of material across 2.7 $km^2$. Initial findings demonstrated the presence of seismic recordings associated with the events. These observations highlight the importance of continued monitoring to reduce risks, enhance preparedness for disasters, and improve infrastructure resilience in active mining areas.

## AS25-0457

# Discussion on the Relationship between Seismic Activity and Deformation Precursors in the Middle Section of Tianshan Mountains in Xinjiang, China

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Guided by the sub-instability theory and premised on the fact that the middle Tianshan Mountains are already in a significantly high-stress state, the study takes into account the fact that the group anomalies of fixed-point deformation in the middle Tianshan Mountains in 2023 can indicate that the phenomenon of coordinated fault movement may have occurred in this region. The deep learning model EQTransformer is used to conduct research on earthquake detection and the frequency of small earthquakes based on the seismic waveform data recorded by the fixed seismic network. An attempt is made to analyze whether there is a significant increase in small earthquake activities in the study area, and to identify whether there is a transformation of the regional stress state from being mainly in the accumulation stage to being mainly in the release stage, so as to determine whether it is in the sub-instability stage. At the same time, a comparative study of earthquake cases is carried out with the Hutubi M6.2 earthquake and the Jinghe M6.6 earthquake. This study attempts to improve the comprehensive prediction for strong earthquakes in the middle Tianshan Mountains and provide support for the assessment of seismic hazards in the middle Tianshan Mountains region in the future.

## AS25-0507

# Seismological Models, Seismicity Patterns and Earthquake Source Characteristics in the Kivu Rift and Virunga Volcanic Province (D.R. Congo)

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The Kivu Rift is located in the bordering region of the Democratic Republic of Congo and Rwanda, in the Western branch of the East African Rift. The active volcanoes Nyamulagira and Nyiragongo in the Virunga Volcanic Province threaten the city of Goma and neighbouring agglomerations with more than 1 million inhabitants today. Eruptions of Nyiragongo caused major disasters in 1977, 2002 and 2021, and destructive earthquakes can also affect the region.

Between 2013 and 2022, the first dense real-time telemetered broadband seismic network in the Kivu Rift region (KivuSNet) was gradually deployed in the frame of several research projects and was fully operational with a sufficient station coverage (>10 stations) from October 2015. Due to the fundamental importance of monitoring the seismicity in this region, substantial efforts were made for setting up this permanent network, which rapidly became the main seismic network of the Goma Volcano Observatory for daily routine monitoring.

This contribution will present the lessons learned from about 7 years of continuous seismic monitoring in the region as well as key seismological information derived from these data, including a robust 1D seismic velocity model and calibrated local magnitude scale. The complete seismicity catalogue (volcanic and tectonic events) has been relocated and the main seismic patterns will be discussed with a special emphasis on how this new knowledge can help the Goma Volcano Observatory in improving its monitoring tasks. Preliminary results for earthquake source parameters will be presented and discussed in the seismotectonic context of the Kivu Rift region.

## AS25-0560

# CsLoc: the combined analysis of crowdsourced and seismic data for fast and reliable seismic location of felt earthquakes

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CsLoc (Crowdseeded seismic Locations) is an innovative method that speeds up the seismic location process by utilizing an external constraint on the location and time of origin of felt earthquakes that is derived from the information-seeking-behavior of witnesses following the ground shaking. For example, if enough people launch the LastQuake app or visit our website, this generates a surge of traffic that is automatically detected and its geographic origin located, resulting in what is known as 'crowdsourced detection' (typically within 15 to 90s of the earthquake occurrence).

In practice, the location of this detection is used to select the seismic stations likely to have recorded the ground shaking, and its time is used to select the time window in which to extract the observed arrival times. Outliers inconsistent with seismic wave propagation are excluded before an iterative seismic location process is initiated. New arrival times are sought at each iteration to allow for data transmission delays. The iteration is stopped when the resulting seismic location meets some predefined quality criteria. We will present the method and show that it works on a global scale, as long as real-time waveforms are available. On average, felt earthquakes are located within 100s of their time of origin and with an accuracy of 10 km.

CsLoc has been operational since July 2022. We will present its capabilities, how it contributes to the rapid crowdsourcing of felt reports (macroseismic data) and the special agreement we have with the Cyprus Geological Survey Department on this topic.

## AS25-0562

# Finally, a new version of the LastQuake application!

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The LastQuake app is designed for witnesses of global earthquakes and focuses only on felt earthquakes. It aims to both provide fast and easy to understand information and to crowdsource witness observations (felt reports) quickly and extensively. While it has been doing a great job since its launch in 2014, now, thanks to the pro bono support of Helena Bukovac & Arian Bozorg, a new interface has been developed and new features added to the Android version released in August 2024. These new features include switching to websocket technology for real-time updates (without manual reloading), automatic translation of comments, the ability to save earthquakes to the "My Earthquake" list, and the ability for users to limit alerts based on distance and magnitude thresholds.

The new version was first implemented on the mobile website for testing, however, the launch of the new app in August 2024 did not go smoothly, partly because it changed the habits of some long-time users and partly because it was plagued by a number of bugs for several months. The situation is now resolved, but the average rating took a hit (from 4.7 to 4.4) and will take time to recover. Nevertheless, this did not affect the number of active users (1.2 million) and with a total of 7 million downloads (Android & iOS), LastQuake remains one of the top earthquake application. The new version will also be released for iOS. We hope that better communication will help to reduce the negative impact of this change.

## AS25-0595

# New generation of sensors in basic and applied research related to earthquake processes

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The scientific and technological advancements of the last decade allowed the scientific community to use a new generation of sensors and analytical solutions in basic and applied research. These new technologies contribute to designing innovative studies and to opening new perspectives for forecasting natural disasters (e.g., earthquakes and volcanic eruptions), mitigating the associated risks.

In the TRANSFORM² project we will develop innovative instruments that will go beyond the state-of-the-art, improving the capabilities of the earthquake science research community for interdisciplinary (seismology, acoustics, geodesy, geochemistry) observational and monitoring purposes. We will exploit recent technological advancements (fiber optic-based systems, fully autonomous low-cost seismic devices, ferroelectric acoustic sensors, high-rate multi-constellation GNSS, automated geochemical sensors) to obtain a new generation of multidisciplinary data that will allow to investigate earthquake nucleation processes in more detail and from different perspectives. Instruments will then be integrated into the Near Fault Observatories (NFOs).

The developed innovative instruments will:

- Provide new observables (geochemical and acoustic sensors) and automatize existing manual procedures for measurements (geochemical sensors)
- Improve data sampling frequency (geochemical and geodetic sensors) and data accuracy (exploiting first-order instrumentation enhancements for geodetic sensors and wide frequency range for acoustic sensors, respectively)
- Implement cost-effective, high-resolution seismic and geodetic sensors
- Allow sustainable, long-term observations in currently non-monitored places as in harsh environments (seismic sensors in offshore sea floor)
- Improve rapid deployment of instrumentation when needed (seismic sensors in postseismic phases)

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## AS25-0619

# P-wave-based earthquake early warning without P-wave detection: continuous monitoring of the UD-component seismic intensity

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Earthquake early warning (EEW) algorithms that predict ground motions directly from the ongoing wavefield (wavefield-based EEW) have been proposed to improve the prediction performance for complex scenarios where source-based EEW algorithms fail to provide accurate source estimates (e.g., large earthquakes with non-negligible finite faults and multiple simultaneous earthquakes). The PLUM algorithm (Kodera et al., 2018) is a wavefield-based approach used in the nationwide Japanese EEW system. PLUM led to several improvements such as the reduction of missed warnings. To improve the PLUM timeliness, Kodera (2018) proposed a P-wave-based PLUM algorithm that uses S-wave intensities predicted from the corresponding P-waves. The algorithm provides S-wave intensity predictions by (1) detecting P-waves based on the ground motion polarization and (2) predicting S-wave intensities if the detection algorithm declares P-wave, adding a constant value (1.0) to the UD-component seismic intensities (assuming that the UD-component intensity corresponds to the P-wave intensity). The prediction performance was influenced strongly by the P-wave detection capability. On the other hand, there were events where overprediction did not occur when the ground motion prediction with the UD-component intensity was applied to entire time windows including S-waves. This implies that the P-wave detection process could be skipped. In this study, we investigated an algorithm that predicts strong motions using the UD-component intensity without the P-wave detection process. We found that the maximum intensities could be predicted from the UD-component intensity within an error of 0.1~0.3 intensity unit, indicating that ground motions could be predicted just by monitoring the UD-component intensity.

## AS25-0672

# Three-dimensional Crust Density Structure and Seismogenic Condition in the North China

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North China is the most seismically active region in eastern China. The crustal density structure of North China holds significant practical importance for understanding the structure of the North China block and the hosting of earthquakes. We derive a new density structure model with a grid resolution of 0.2°×0.2°×5 km for the depth range of 0–45 km based on high-precision gravity data and several seismic tomography models of crustal structures in North China. A gravity inversion algorithm with Bayesian optimization is used. The new model aligns well with the characteristics of structural zoning, and the high-gradient crustal density zones at the epicenters of three major earthquakes above magnitude 7 are prominent.

## AS25-0729

# The ISC Bulletin: How we create the Earth's most comprehensive seismic bulletin

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The Bulletin of the International Seismological Centre (ISC) is widely regarded as the most comprehensive record of the Earth's seismicity, and has been in production for over 6 decades. With the support and cooperation of more than 150 agencies worldwide we are able to integrate and combine data from many sources, from global agencies with permanent networks to local temporary deployments. Our position as a not-for-profit and non-governmental entity allows us to create a unique product that is then freely provided to the global community. The ISC Bulletin is used by thousands of seismologists worldwide for seismic hazard estimation, for tectonic studies and for regional and global imaging of the Earth's structure. It served as a major source of data for such well known products as the ak135 global 1-D velocity model and the ISC-EHB Bulletin and presents an important quality-control benchmark for the Comprehensive Nuclear-Test-Ban Treaty Organization.

This poster will give an overview of the ISC Bulletin and explain:

- How is the ISC Bulletin is created and reviewed?
- Who provides when, how much and what kind of data?
- What use does the ISC make of waveform data and contribute to the ISC Bulletin? (depth phases, focal mechanisms, source time functions, picking of under represented areas etc.)
- How many phase arrivals, amplitude data, seismic stations, ISC reviewed events can be found in the ISC Bulletin?

## AS25-0732

# Data-driven based b-value calculation method and its applications

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Accurate calculation of seismicity parameters is crucial in earthquake engineering, geodynamics research, and seismic hazard analysis. However, due to the high spatial and temporal variability of intraplate seismicity and significant differences in seismic monitoring capabilities, this remains a significant challenge. There is an urgent need for precise seismicity parameter calculation techniques.

Traditional sliding windows method for calculating *b*-value, which introduce significant subjectivity. To address this issue, we developed a novel parameter-free calculation method based on data-driven approach. We adopt the continuous distribution function of MFD (Ogata and Katsura, 1993), establish a large number of randomly partition models, design effective model selection criteria, and select the best models to form an ensemble model and obtained the ensemble median *b*-value as the final result. The median absolute deviation (MAD) is used to represent the uncertainty of the *b*-value. It simultaneously estimates the *b*-value and other two parameters (μ and σ) that can be combined to describe the completeness of the earthquake catalog, allowing for the maximization of data utilization during the dynamic evolution of the minimum completeness magnitude.

This method provides accurate seismicity parameters for addressing spatial heterogeneity in intraplate seismic zones, offering foundational data for earthquake engineering and geodynamics. It can further be used to investigate the processes of earthquake nucleation and occurrence. This technology offers an effective tool for simulating seismicity and analyzing seismic hazards.

## AS25-0739

# High VP/VS region beneath Mt. Tokachi-dake due to dehydration reaction of the mantle wedge

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Detailed velocity structure models of the Earth's interior using seismic tomography are often used to precisely locate magma chambers and magma conduits. In this study, we developed an analytical tool that uses a simultaneous iterative reconstruction technique (SIRT) to minimize the variance of slowness perturbation between seismic paths.

In the northern part of Japan, in Hokkaido, the Pacific Plate subducts from the southeast to the northwest along the Hidaka Mountains, Kitami Mountains, and Teshio Mountains. At the center of these mountain ranges is the active volcano Mt. Tokachi-dake. Mt. It began its activity 2 million years ago, and in the past 150 years alone it has erupted in the Ansei (1857), Meiji (1887–1888), Taisho/Showa (1926–1928), Showa (1962) and Showa/Heisei (1988–1989) eras. The eruption style is mainly Strombolian, the mountain body is composed of basalt and andesite, and it is thought that primary magma from the mantle is strongly involved.

In this study, we clarified the existence of a conduit-like high VP/VS region in the mantle wedge beneath Hokkaido, extending from directly beneath Mt. Tokachi-dake to the region where the seismic activity of the Pacific plate slab drops sharply at depths of 150 km or more. This region is thought to be a region where the mantle wedge is melting due to dehydration reactions.

## AS25-0858

# Coastal Elevation Changes and Large Earthquakes in Chile

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Fault activation produces significant deformation in its surroundings. Because Chile presents a high productivity rate of large earthquakes it is an ideal laboratory to observe these changes; extreme examples are those associated with the 1960 $M_w$=9.5 event: 6 m of uplift to nearly 3 m of subsidence.

The first historical accounts of coastal elevation changes in Chile associated with earthquakes, are those reported in the travel journal of Maria Graham for the 1822 event. Thirteen years later, the observations by Darwin and Fitz Roy evidenced the uplift of several islands close to Arauco Peninsula. These observations are complemented by reports of coastal subsidence for both the 1868 and 1877 events in southern Peru and northern Chile and coastal uplift for the 1906 event. Re-observation of leveling lines have evidenced crustal vertical movement for the 1939, 1960, and 1985 events. For later events, satellite technologies have allowed determination of temporal changes and the spatial extent of the inland deformation as well. At present, it is possible to detect and accurately determine relatively minor horizontal changes, at a few mm level.

Comparison of the 1822, 1906 rupture area with more precise determinations for the 1985 event, allow inferences of a variable mode of rupture in Central Chile. Updated plate locking models obtained by GNSS velocity estimations in the region, together with GNNS derived slip distribution for the April 24, 2017, M6.9 event are used to interpret the current state of preparation of the next large event in the area.

## AS25-0875

# Analyzing the Coulomb Stress Change and Triggering Mechanism of Saurashtra Earthquake, November 6, 2007 (Mw 5.0), Gujarat-A potential implications

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Gujarat, a seismically active region in western India, has experienced significant earthquakes, including the Mw 7.8 earthquake in 1819 and the Mw 7.7 earthquake in 2001. The Gujarat Seismic Network (GSNet), operated by the Institute of Seismological Research (ISR) since 2006, monitors regional seismic activity using 50 broadband seismographs and 49 accelerographs. On November 6, 2007, a moderate earthquake (Mw 5.0) near Talala, in the Girnar Mountains, triggered 1,300 microearthquakes, including 325 with magnitudes ≥ 1.5, lasting until January 10, 2008. A foreshock (Mw 4.8), occurring 9 hours before the main shock, caused some damage. The study suggests that the main shock's coseismic slip induced static Coulomb stress changes, increasing aftershock activity. On October 5, 2008, a moderate earthquake (Mw 4.3) occurred in an area of positive Coulomb stress, supporting the idea that aftershocks were triggered by the main rupture. Analysis of stress changes along the foreshock plane revealed that aftershock activity continued due to stress transfer. The study assessed various factors like temporal decay, b-value, spatial fractal dimension (D), and slip ratio. The b-value of 1.18 indicated fewer large aftershocks, suggesting crustal heterogeneity. A high p-value (1.10) pointed to rapid aftershock decay, and the spatial fractal dimension (D) of 2.21 indicated a random distribution of aftershocks. These insights contribute to understanding seismic dynamics in Gujarat and future seismic risks.

## AS25-0880

# Finite-frequency joint tomography of body and surface wave data in the West Pacific region

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Conventional body-wave traveltime tomography based on ray-theory can be considered an infinite-frequency approach, while a recent full waveform inversion (FWI) utilizes a broad frequency range to fit selected parts of seismograms. However, in practice, FWI requires substantial computational resources, often limiting the model domain size, dataset size, and frequency range. A more computationally efficient alternative is a joint body- and surface-wave tomography, which simultaneously incorporates body-wave traveltimes and surface-wave dispersion measurements. In this study, to further reduce the gap between the joint inversion and FWI, we incorporated finite-frequency sensitivity kernels for surface-waves by Yoshizawa & Kennett (2004) into the formulation of Fang et al. (2015) for a one-step inversion method for surface-wave traveltimes without constructing the phase velocity maps. For body-wave data, we followed Obayashi et al. (2013) who employed a hybrid approach combining finite-frequency (Dahlen et al., 2000) and ray-theoretical kernels (Inoue et al., 1990).

We applied this method to construct the 3-D shear wave velocity structure beneath the Ontong Java Plateau (OJP) region. The body-wave dataset was obtained from the "OJP Array", the broadband ocean-bottom seismic investigation (Suetsugu et al., 2018), including manually picked S traveltimes and multiband differential traveltimes between stations. For surface-wave data, we used Rayleigh and Love wave phase velocity dispersion. We will present the resulting velocity structure in comparison with previous tomographic studies in the OJP region, both the multi-frequency traveltime tomography (Obayashi et al., 2021) and the radially anisotropic shear wave tomography model (Isse et al., 2021).

## AS25-0917

# Temporal evolution of moderate magnitude, tectonic earthquake series at Hornsund, Spitsbergen

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Tectonic seismicity in the Svalbard Archipelago, European Arctic, is observed episodically, in specific source regions. One of them is the area of the Hornsund Fjord, Spitsbergen, where observations date back to the early 1980s, enabled by the availability of seismic sensor(s) at the Polish Polar Station. Among recent earthquake activity of adequately large magnitude to locate accurately with the regional seismic network and obtain moment tensor solutions, are two moderate sized earthquakes that occurred at the southern coast of the fjord (4 July 2015, M 4.5; 31 May 2017, M 4.7). Each is associated with clustered seismicity, the 2015 main event being followed by an aftershock sequence, and the 2017 one exhibiting both foreshocks and aftershocks.

Template matching facilitated the compilation of detailed catalogues, with detection and magnitude thresholds significantly reduced by the proximity of the source region to the broadband seismic station HSPB (~ 10 km), offering a high-resolution image of the temporal evolution of the two series. Despite the similarity in size and source properties of the mainshocks, as well as the geographic proximity and partial overlap, the two processes unfold differently. The 2015 activity is a compound series manifested in three distinct branches, lacking seismic precursors, whereas the 2017 series commence with an accelerating cascade of foreshocks distributed within 10 days before the mainshock, aftershocks occurring within a single branch.

We present design and implementation of the workflow employed to populate our catalogues and the temporal characteristics and statistical properties of the two seismic series.

## AS25-0966

# How dense seismic networks enable identification and monitoring of supersonic objects in the atmosphere

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Originally designed for earthquake monitoring, dense seismic networks such as the Epos-France Permanent Broadband Network (RLBP) now enable the identification and localization of atmospheric events such as meteors and supersonic aircrafts. This is achieved by seismic-acoustic coupling, where shock waves generated by meteors can be recorded by seismic sensors on the ground. We use the Reverse Time Migration (RTM) method (Walker et al., 2010) to accurately identify acoustic sources of interest. The method uses a "grid search" approach to evaluate potential source points by ordering seismic traces by distance and calculating the sum of envelopes of the seismic signals. The integration of atmospheric data from the ECMWF model and an attenuation law optimizes this process by selecting the most relevant seismic stations, increasing the signal-to-noise ratio, and improving the localization accuracy. We present several case studies, including meteors fragmentation in the atmosphere, supersonic aircraft and the eruption of Stromboli volcano on July 11, 2024, which allow precise dating of the paroxysm and localization to within a few kilometers of the Sciara del Fuoco (i.e., ground truth validation). This approach, which allows the localization of a meteor without direct visual observation, regardless of weather conditions or time of day, is intended to complement the optical observations of the FRIPON camera network. Ongoing research, which we also present, aims to further refine the method to include the detection of other atmospheric phenomena, such as satellite debris, thereby enhancing the seismic network's ability to monitor an ever-widening range of events.

## AS25-1058

# Understanding Surface-Wave Diffraction Patterns: Holographic Effects in Earthquake and Ambient Noise Wavefields

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Stripe-like patterns of wavefield deviations of earthquake surface waves have been observed at large dense seismic networks, namely USArray, AlpArray and AdriaArray. These patterns elucidate diffraction and interference effects, indicative for the interaction of the direct wave and an additional wavefield emitted by a strong scatterer outside of the network. Ambient noise correlation wavefields also exhibit this distortion when an isolated noise source radiates energy from a particular direction. In both cases, the direct wave is biased by interference with an additional wave. Another recording of such interference effects are optical holograms, where one wavefield interacts with the objects to be imaged (the "object wave") and the other does not (the "reference wave"). We use AxiSEM3D to simulate global wavefield propagation through a model with multiple scatterers. The synthetic seismograms, computed for hundreds of stations, demonstrate how the characteristic pattern emerges in amplitudes and other quantities. Likewise, ambient noise simulations that consider an isolated noise source allow us to reproduce the observed pattern of variations in correlation wavefields. These interference patterns can be understood as holograms, where the direct wave from the earthquake source and wave scattered at structural anomaly take the role of reference and object wave, respectively. In correlation wavefields, the wavefield contributions by isolated noise source and virtual source behave in the same manner. Our results suggest that interference of seismic wavefields is 1) a potential source of bias in imaging applications and 2) allows for recognizing strong structural anomalies and noise sources, exploiting holographic principles.

## AS25-1076

# The ISC earthquake toolbox for MATLAB

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The ISC Bulletin is the definitive collection of global earthquake observations created by reviewing data reported to the International Seismological Centre (ISC) by ~150 agencies in ~100 counties. In addition to information about the earthquake hypocentres, the bulletin also includes phase, magnitude and moment tensor information associated with each event. The bulletin is freely accessible, searchable and downloadable through the ISC website (www.isc.ac.uk/iscbulletin). We have developed a new publicly available method for obtaining data from the ISC Bulletin in a MATLAB environment "The ISC Earthquake Toolbox for MATLAB" which is available via the MathWorks file exchange and GitHub (github.com/tomgarth/ISC_Earthquake_Toolbox). We will demonstrate the below functionality and display example figures created using the toolbox. The toolbox provides a graphical user interface (GUI) allowing the user to select specific times, regions and magnitudes for which earthquake parameter data will be downloaded from the ISC Bulletin into MATLAB data tables. Contained within the toolbox are live scripts demonstrating enhanced functionality for plotting and analysis, and a tutorial explaining how to interrogate the ISC Bulletin data using the developed GUI. Examples of toolbox functionality include comparing hypocentres reported by multiple agencies, plotting events alongside global fault maps, creating b-value and magnitude of completeness plots for user defined areas, creating plots comparing magnitudes from multiple reporters and plotting reported focal mechanisms on maps and in transects. Additionally, the toolbox contains the ability to plot moment tensors within MATLAB maps and create an interactive 3D visualisation of any reported focal mechanism.

## AS25-1086

# Combining earthquake bulletins in the West Bohemia/Vogtland swarm region to study the shape brittle-ductile boundary

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The Vogtland/West Bohemia region, which extends across the border between Germany and the Czech Republic, is one of the most geodynamically active areas in Europe. This activity manifests as massive $CO_2$ degassing and persistent mid-crustal earthquake swarms, which have been hypothesized to be indicative of deep-seated magmatic activity. Since 1984, most swarm activity in this region has been concentrated around the Czech village of Nový Kostel, near the border with Germany and specifically the German states of Saxony, Bavaria, and Thuringia. As a result, several institutions, each using its own seismic network and processing flow, work to produce catalogs of regional seismicity. Due to these differences, the various agencies may detect or miss different events. In this study, we aim to combine all earthquake observations provided by institutions operating in the Vogtland/West Bohemia region to obtain a more comprehensive view of seismicity. Specifically, we focus on the depth distribution of the deepest events near the focal zone of Nový Kostel, as previous studies have proposed that the hypothesized deep magmatic activity may cause regional variations in the depth of the brittle-ductile boundary. We develop a unified earthquake catalog using nearly 16 years of P- and S-wave arrival time observations from four seismic networks: the Czech WEBNET and the German SaxonNET, BayernNetz, and Thüringer Seismologisches Netz. Next, we invert the combined traveltime dataset using the SIMULPS2023 algorithm to refine the regional P-wave velocity model and jointly relocate earthquakes.

## AS25-1090

# High-resolution 3-D Seismic Tomography of 2015 Gorkha Earthquake Source Region: Geodynamic Implications for Major Crustal Earthquakes and Hazard Assessment Zones

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We present comprehensive and high-resolution tomographic image of 2015 Gorkha earthquake source region based on traveltime inversion of local and regional earthquake data. Our tomographic image shows systematically arranged high and low-velocity zones, depicting heterogeneous crustal architecture with substantial variations along-strike as well as across-strike of the Nepal Himalayas. Our tomographic model closely correlates with varying rupture processes and their relationship to the tectonic setting accompanying the main shock, inferring role of crustal heterogeneities in controlling source rupture dynamics. We imply that the geometry of MHT and heterogeneous architecture of seismogenic crust govern earthquake processes. Low-velocity anomalies in shallower part may correspond to alignments of faults/tectonic features representing weak zones of seismogenic crust and high-velocity anomalies may represent hard and rigid blocks. This suggests that earthquakes normally initiate at the interface/boundary of high- and low-velocity anomalies separating two anomalous zones of structural heterogeneities. High-velocity blocks have relatively higher mechanical strength and hence act as stress concentrators. We observed that main shock of Mw 7.8 nucleated in the mid-crustal ramp zone of MHT in a zone of relatively lower crustal thickness. As rupture propagated eastward along a down-dip portion of MHT, it reached higher crustal thickness and higher seismic velocity where the Mw 7.3 event triggered. We infer that this may have blocked the rupture propagations towards east-southeastward and hence controls spatial limits of rupture. We imply that first earthquake led to an increase in strain on a more rigid body that ruptured when it was strained beyond its elastic limit.

## AS25-1100

# Supplementary ISC services for seismology: there to help!

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The primary mission of the International Seismological Centre (ISC) is to produce the most long-term and complete list of instrumentally recorded earthquakes and other seismic events on a global scale by running seismic event data exchange with ~150 networks in ~100 countries. The ISC Bulletin, the ISC-GEM catalogue, the ISC-EHB and the GT datasets are a direct result of this work.

In addition, the ISC provides several supplementary datasets and services useful in geophysical research. The International Registry of Seismograph Stations provides positions and reporting statistics of stations that shared parametric measurements since 1904. The Electronic Archive of Printed Station/Network Bulletins holds the most comprehensive of all available global collections of observatory catalogues, including station parameters, produced until 1998. The invited Network Articles in the Summary of the ISC Bulletin describe the history, current status, and procedures used by these networks to determine locations of seismic events, magnitudes, source parameters, event types, etc. So far, the articles from 19 networks regularly reporting to the ISC are accessible via relevant agencies in the ISC Agency Registry and their hypocentre solutions in the ISC Bulletin. The ISC Event Bibliography provides references to scientific publications that describe seismic events (1904–2025) within the region of interest. The ISC Seismological Dataset Repository makes individual researcher's datasets openly available long term and thus also helps to provide access to data used in scientific publications. The International Seismological Contacts help seismologists find colleagues in other countries and thus facilitate joint research and capacity building worldwide.

## AS25-1188

# Seismicity and Vp and Vp/Vs models around the Mefite d'Ansanto deep-CO2 degassing site (Southern Apennines, Italy)

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Mantle-derived fluids play a primary role in the generation of large upper crustal earthquakes in extensional domains. Here, we focus on the Mefite d'Ansanto degassing site, the largest low-temperature non-volcanic deep-CO2 emission site in the world (about 2000 tons per day), located at the northern tip of the Mw6.9 1980 Irpinia faults in the Southern Apennines (Italy). The area, characterized by high heat flow and pervasive CO2 rich fluids circulation, experienced strong historical earthquakes (M6+) but it is characterized by low background seismic rate, with respect to the nearby Sannio and Irpinia regions.

To investigate this key-sector of the Southern Apennines, we collected high-quality microseismicity data during a two-year dense temporary passive survey (2021 to 2023). Starting from about 300 manually picked earthquakes, we applied a template-matching algorithm to detect low-magnitude seismicity. We computed a best fit 1D Vp velocity model of the area through a non-linear technique, and 1D earthquake locations using the probabilistic non linear location method NonLinLoc.

The catalog is composed of about 1000 earthquakes (-0.7<ML< 3.0). Most of the seismicity has small magnitude (ML<1), confirming the low seismic rate of this area compared to the adjacent regions, and occurs in small clusters (sometimes along small faults) characterized by either short-lived or sustained seismic activity. We also present a new 3D Vp and Vp/Vs seismic tomography model of the area, that helped us to investigate the relationship between seismicity and crustal structure in this crucial sector of the Southern Apennines belt.

## AS25-1192

# The Marsquake Service Reference Catalogue

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The Marsquake Service (MQS) is finalizing the release of the reference catalogue of Martian seismicity recorded by NASA's InSight mission. Previous catalogue versions listed over 1300 events classified by their observed frequency content into i) low frequency (LF) and broadband (BB)—the key events for constraining interior structure, ii) 2.4 Hz and high frequency (HF)—representing the majority of events with weak signals and enigmatic origin, and iii) very high frequency (VF) events, including several nearby impacts.

Since the last release in April 2023, MQS has reviewed the entire data set, also using denoised data sets to refine phase picks, back-azimuths, and ensuring consistency across the catalogue. MQS has revised the frequency-based event classification into three interpretation types:

i) Tectonic events, mostly located ~30º east of InSight in Cerberus Fossae and in few other regions with deeper sources, include most LF and BB events with low corner frequencies.
ii) Swarm events are a subset of HF and 2.4 Hz events clustered in ~44º distance with shallow seasonal sources, though their source region remains speculative; this group has been significantly expanded through deep learning techniques.
iii) Meteorite impacts, characterized by high corner frequencies, encompass VF events, several large BB events, and HF/2.4Hz events located outside of the swarm region.

The reference catalogue includes over 1900 events with improved locations and new interpretation types, providing a more comprehensive view of Martian seismicity observed by InSight.

## AS25-1243

# Regional variation of b-value in the Azores revealed by earthquake clusters: tectonic implications and critical assessments of existing statistical methods

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Seismicity in the Azores originates from both volcanic and tectonic activity in the archipelago's complex tectonic setting, featuring a triple junction, an oceanic plateau and the active Terceira Rift. Characterizing earthquake statistical parameters like b-value, often interpreted to be inversely related to differential stress, allows to distinguish between regional earthquake sources. However, among many other factors, these parameters are affected by uneven coverage and the occurrence of time-dependent events like aftershocks and volcano-tectonic swarms, which are frequent in the Azores.

This study introduces a new approach to regionalisation: identifying and statistically analysing seismicity clusters, which represent seismogenic zones. Furthermore, the study critically evaluates and compares some existing approaches to estimating completeness magnitude and fitting the Gutenberg-Richter law. The presented outcomes result from methods which have been modified in novel ways to optimize their functionality for regional catalogs. A comparison of the results before and after Reasenberg-declustering allows to investigate the effect of time-dependent events on earthquake-statistical parameters and to characterize long term background seismicity in the Azores.

The results demonstrate that b-value increases near volcanic centres, expressed as islands and seamounts. The Terceira island is an intriguing outlier, yielding a b-value of ~1 despite abundant historic volcanic activity. As expected, declustering the data prior to analysis reduces regional heterogeneity. The resulting background seismicity reveals a westward increase in b-value, implying a differential stress decrease toward the triple junction. Ultimately, this study highlights the trade-off between 1) data resolution and 2) catalog homogeneity and Gutenberg-Richter law quality in seismicity characterization.

## AS25-1264

# Teleseismic P-wave and water-column reverberations for depth determination of South Atlantic earthquakes

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Transform faults are a fundamental aspect in investigating the dynamics of the oceanic lithosphere, especially regarding the mid-oceanic ridges. Parameters of oceanic earthquakes are an essential source of information on tectonophysics processes. However, estimating focal depth has significant difficulties due to the insufficient continental distribution of instruments at teleseismic distances. Earthquake focal depths may be computed using phase depths (e.g., pP, sP, sS, etc) at teleseismic distances. Still, depth value ranges, low signal-to-noise ratio, and rupture duration cause inaccuracies in those estimates. In this way, we implemented the methodology described by Huang et al. (2015) based on water reverberations using stacked seismograms with a grid search approach for simultaneous estimation of Z and the sea floor depth (H). Tests indicate the method was effective for synthetic data and earthquakes of the South-Equatorial Atlantic in different conditions. Lastly, the results suggest that the radiation pattern is central to the focal depth estimation.

## AS25-1373

# A new ground truth event catalog for validation of regional seismic velocity models in Canada

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Location uncertainty of seismic events can be assessed through careful study of "ground truth" (GT) events of known location, depth and timing. GT datasets are also critical for the validation of seismic velocity models used in routine event locations by network operators. Given the low station density in some regions of the Canadian National Seismograph Network (CNSN), many moderate-magnitude mining-induced events fall short of the secondary azimuthal gap constraint proposed by Bondar et al. (2004), even though the location, depth and/or origin time have been confirmed by the mine operator. We present a process for qualifying these as GT events, including an assessment of epicentral uncertainty associated with both the estimation of origin time for events with known hypocentre, and the assignment of epicentres based on satellite imagery of open-pit operations. The recent deployment of the Canadian Earthquake Early Warning (EEW) network of accelerograph stations furthermore offers improved station density and ray path coverage. The result is a GT catalog of locally and regionally recorded earthquakes, mining-induced events and refraction explosions which maximizes ray path coverage for crustal seismic phases across the Canadian landmass. Our approach is conservative and yet greatly increases the number of reliable GT ray paths available for validation of a Regional Seismic Travel Time (RSTT) model for Canada that is currently under development.

## AS25-1394

# An extension of the non-stationary ETAS model

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The epidemic-type aftershock sequence (ETAS) model, proposed by Ogata [JASA, 1988], is extensively utilized for analyzing the temporal occurrence patterns of earthquakes. In the original ETAS model, the background seismicity is assumed to be constant in time, but it was represented by a polynomial function [Iwata & Katao, GRL, 2006] or a piecewise linear function [Kumazawa & Ogata, JGR, 2013] in order to consider the non-stationarity of the background seismicity.

In Kumazawa & Ogata [2013], the (modified) ETAS model where the background seismicity is represented by the Omori-Utsu formula [Utsu, 1961, Geophys. Mag.] was also examined. Following that study, the ETAS model, where the background seismicity is given as the sum of the Omori-Utsu formula and a piecewise linear function, is explored in this study. Similar to Kumazawa & Ogata [2013], the breaking points of the piecewise linear function were taken at the occurrence times of each of the earthquakes. Then, using a Bayesian approach with a smoothness constraint, the coefficients of the function were estimated. The strength of the smoothness constraint was determined by means of the maximization of a marginal likelihood.

As a demonstrative example, the explored model was applied to the swarm-type sequence that occurred in the aftershock area of the 2018 Hokkaido Eastern Iburi earthquake, which began in early October 2018. The ABIC value of the explored model is 0.9 lower than that of the ETAS model with only the piecewise linear function, suggesting that the explored model exhibits slightly better performance.

## AS25-1425

# 3D P-wave attenuation tomography of the Tonga-Lau subduction system with a transdimensional Bayesian Monte-Carlo approach

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Attenuation, resulting from Earth's anelasticity, exhibits sensitivity to thermal and rheological characteristics and thus plays a vital role in constraining Earth's interior. However, unlike seismic velocity tomography, seismic attenuation tomography extracts energy dissipation information, making it more complicated to conduct. Traditional methods often invert for multiple parameters simultaneously and then apply linearized techniques for 3D model inversion. In this study, we first incorporate independently constrained source parameters to invert for the path average attenuation operator, t*, thereby minimizing the trade-offs between path and source terms. Then, based on the refined t* dataset, we apply a Bayesian Markov chain Monte Carlo (MCMC) approach to image the 3D attenuation structure. The non-linear, transdimensional MCMC method accommodates diverse model complexities and yields a robust uncertainty map. We test this approach in the fast-converging Tonga subduction zone and its adjacent Lau back-arc. The tomography results reveal high attenuation anomalies in the Tonga-Lau back-arc mantle and a region of elevated attenuation in the mantle transition zone. Combined with existing velocity models, our results quantitatively suggest a southward decrease in melt porosity along the back-arc.

## AS25-1439

# Deep Learning-Driven Spatio-Temporal Analysis of Earthquake Precursory Signatures in the Sumatra-Andaman Region

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Earthquake forecasting is highly complex due to its heterogeneous nature. This research focuses mainly on analyzing spatiotemporal trends of earthquake precursory signatures in the Sumatra-Andaman region. The dataset spanning from 1921 to 2025 has been taken for analysis. The study involves micro shocks analysis to achieve deeper insights in earthquake nucleation so as to understand the earthquake preparation processes. A spatiotemporal analysis of micro shocks is conducted through clustering of seismic events based on latitude, longitude, and depth over each lunar year, helping to identify the nucleation zones where seismic stress may be accumulating. From the results, it is inferred that earthquake preparation processes may occur 1–3 lunar months prior to the higher magnitude earthquakes. Also to address the prediction of earthquake magnitude, this project aims to investigate the scenario of same study region using deep learning models- Long Short-Term Memory (LSTM), Bi-directional LSTM (Bi-LSTM), and Transformer models with self-attention mechanisms-to predict earthquake magnitudes based on key seismic indicators. Feature engineering is performed on the dataset and these models were trained and validated using earthquakes in the same confined study region spanning 1921 to 2025. This interdisciplinary approach improved understanding in earthquake nucleation process and earthquake prediction accuracy of 95% with a low MAE of 0.0429.

## S02 International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

### AS25-0020

# Advance in Seismic Observation Networks around Syowa Station, Antarctica

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Seismic observation at Syowa Station (69.0° S, 39.6° E; SYO), Antarctica started since 1959 associated with the International Geophysical Year (IGY; 1957–1958) campaign. Since the establishment of INTELSAT telecommunication link, digital waveform data have been transmitted to the National Institute of Polar Research (NIPR) for the utilization of phase identification more clearly. Arrival-times of the teleseismic phases, such as P, PKP, PP, PKKP, S, SKS have been detected with reporting to the International Seismological Centre (ISC), then published as the "Data Reports" by NIPR. Seismic phase travel time data incorporated with annual catalogs of detected teleseismic earthquakes are particularly focused on, besides with data utilization for public usage. Recorded waveform data, seismic-phase travel-times and corresponding earthquake catalogs have sufficient quality for many analyses involving dynamics and structure of the Earth viewed from Antarctica. The continuously recorded data for a few decades after IGY have been utilized not only to the lithospheric studies but also to the Earth's deep interiors, which has significant contribution to the Federation of Digital Seismological Networks (FDSN) from high southern latitude. The initiative during IPY2007–2008 was a unique opportunity for implementing the FDSN, in addition to the bi-polar observing network; the POLENET. From the AGAP/GAMSEIS data at the IPY, moreover, local signals involving ice sheet and atmosphere variations were recorded, with a significant number of teleseismic events. In this presentation, advances in seismic observation networks around the SYO, in LHB and surrounding regions in Antarctica are introduced associated with scientific linkages other regional and global seismic networks.

## AS25-0021

# Evolution and Optimization of the Raspberry Shake Data Center: Managing the World's Largest Real-time Seismic Network

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The Raspberry Shake Data Center (SDC) has undergone a comprehensive redesign in 2024 to meet the demands of both a large network and its ongoing rapid growth. Currently managing 2,500 online stations, ~7,000 channels, each streaming at 100 samples/second, the SDC supports all aspects of what it means to host and manage the world's largest real-time seismic network. The new infrastructure has been architected with an eye towards gracefully handling the network's future expansion, anticipated to exceed 10,000 stations.

We present the technical infrastructure and architectural solutions implemented to handle massive-scale data acquisition and distribution. Given the scaling requirements for a seismic data network intended to be up and available 24/7/365, open-source technologies in the seismological communities alone are not able to deliver a solution satisfying the network's myriad requirements. This led to the development of custom C/C++ solutions optimized for high-throughput data handling, automatic fail-over and recovery of critical systems, the ability to easily scale the server-side infrastructure both vertically and horizontally, and more. The integration of gempa GmbH's CAPS software has been crucial in enabling efficient data distribution at large scales.

This presentation details the implementation of multi-level redundancy systems and discusses how a citizen-science initiative evolved to require enterprise-level data center capabilities. We focus on the technical challenges of scaling real-time seismic data acquisition and distribution beyond conventional boundaries, highlighting solutions for managing high-volume data streams, all the while maintaining system accessibility, reliability, and integrity.

**Keywords**

seismic networks, real-time data acquisition, data distribution, network scaling, data center infrastructure, raspberry shake

## AS25-0083

# Instrumentation of sensors for a regional earthquake early warning system for Uttarakhand, India

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The Himalayas, being the youngest mountain range, are highly prone to earthquakes. Uttarakhand, a Himalayan state in India located in the central seismic gap, initiated a project to develop a regional Earthquake Early Warning System (EEWS) to mitigate earthquake impacts and improve preparedness. This paper outlines the research and operational tasks involved in developing regional EEWS for Uttarakhand (UEEWS), including instrumentation of 170 sensor in seismically active regions, network configuration for data transfer from sensors to central server, and continuous seismic data preprocessing, such as baseline and instrument response correction, site-effect offsetting, and filtering, before the use of data in further processes. Central server has been established with necessary hardware and software. This involved the compilation and execution of open-source codes, configuration of specific EEW parameters, setting threshold values for certain variables, incorporating phase-picking algorithms, and implementing approach to locate earthquake hypocenter and estimate magnitude based on EEW parameters.

When an earthquake occurs, UEEWS generates reports and issues warnings through siren units installed in public buildings and the "BhuDEV" mobile app. Since its launch on August 4, 2021, UEEWS has successfully issued warnings for light to moderate earthquakes, and even for earthquakes about 100 km outside the instrumented region. However, no strong earthquakes have occurred in the instrumented region since its launch.

The authors contributed significantly to research, modeling of parameters, algorithm design, programming for central server, and operation and maintenance of full-fledged UEEWS at EEWS Laboratory, Indian Institute of Technology Roorkee (IIT Roorkee).

**Kewords**

Himalayas, Instrumentation, Earthquake Early Warning System, Uttarakhand

## AS25-0190

# New Zealand-Aotearoa GeoNet event monitoring systems rework, evolution and challenges

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Aotearoa-New Zealand is prone to wide-ranging geological hazards. Since 2001, GNS Science Te Pū Ao has led and operated the GeoNet project, dedicated to identifying, studying, preparing for, and responding to these hazards. GeoNet operates a comprehensive network of instruments, including around 200 velocimeters and 300 accelerometers, which facilitate rapid multi-hazard event detection and data curation for the public, scientists, and response functions. Over the past decade, GeoNet has successfully developed its instrumental network and modernized its services, in addition to introducing a 24/7 manned multi-hazards monitoring center.

GeoNet faces several new challenges today, and is focusing on more agile detection systems with more complete and timely earthquake source information while maintaining state-of-the-art monitoring techniques, services, and curating an increasing amount of data. As part of that, GeoNet is reviewing its SeisComP earthquake location system architecture, design and scope and seeking to collaborate in new ways. The list of demands on the earthquake architectures is varied: from changing seismic networks, incorporating new instrumentation to introducing new monitoring processes and information content such as magnitudes and moment tensors, potentially delivering regional and targeted local instances, and finally implementing next-generation techniques and processes.

Here, we will focus on the short-term topics that the GeoNet project is implementing: the earthquake location systems architecture overhaul into rapid and review instances and implementing a new NZ local magnitude in operations. We also discuss what GeoNet operational and GNS research teams are prioritizing for the future.

## AS25-0206

# Development of Low-Cost Seismic Monitoring System for Field Application in Bangladesh

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Due to its geographical location close to the plate boundaries of Indian plate colliding with the Eurasian plate to the north and east, Bangladesh is in considerable seismic risk. The seismic zone coefficient (Z) varies from 0.12 to 0.36 as per Bangladesh National Building Code 2020. Under internal research funding at Bangladesh University of Engineering and Technology (BUET), a project is in progress as a joint collaboration between the Civil Engineering Department, and Electrical and Electronic Engineering Department to develop a seismic monitoring system comprising of low-cost accelerometers to be designed and manufactured at BUET using low-cost components. Key components of the device have been selected from available options of accelerometer sensors and microcontrollers. Next the device is designed and programmed to work as a self-sufficient unit. Data will be recorded on a local storage, and also uploaded to a cloud system at frequent time intervals so that remote access to the data is possible. The accelerometer is programmed to issue a warning message at a certain threshold value of acceleration. The device will have UPS/Battery to cater for power outages of several hours. The accelerometers will be installed at cities in the north, north-east and south-east of the country, in addition to the capital city of Dhaka which is located in the central region. Hence, the installed accelerometers can be utilized as early warning devices in Dhaka for distant earthquakes. This paper will present key aspects of the prototype low-cost accelerometer devices, in-laboratory device calibration, and recorded seismic data.

## AS25-0212

# International collaboration to sustain an international monitoring system

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Collaborating with station operators and representatives from national data centres, as well as international experts, network operators and equipment manufacturers has played an important part in developing a sustainment strategy for the International Monitoring System (IMS), operated by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). From questionnaires for competition by IMS station operators and representatives from national data centres, to creation of a guidance committee, as well as in depth discussions with manufacturers have assisted the CTBTO to identify the expected lifespan of the equipment installed at the stations and the complexities that should be considered when developing long term sustainment strategies for monitoring networks. This pool of international sources of information have proved to be crucial as “sounding boards” for guiding our understanding of the best methods to utilize within the sustainment strategy.

## AS25-0214

# Bulgarian Seismological Network—development and current status

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The seismological observations on the territory of Bulgaria have traditions of more than 120 years. The beginning of Bulgarian seismology dates back to 1891. The period of Bulgarian historical era ends in 1905 when the seismograph of Omori-Boch type was installed in the first Seismological Station in the town of Sofia. In the period 1961–1979, six seismic stations were run. At the end of 1980, the National Operative Telemetric System for Seismological Information (NOTSSI) was put in operation consisted 21 short period one component seismic stations deployed on the territory of the country. It was a key point in seismic monitoring in Bulgaria. In 2006 the digital seismological equipment was installed at all stations of the network and a data center with real-time automatic and interactive data processing was organized. Nowadays, the number of seismic stations increased significantly and it is 41.

NOTSSI as a part of the National Institute of Geophysics, Geodesy and Geography (NIGGG) of Bulgarian Academy of Sciences has been in continuous operation during the last 45 years. The network provided high quality seismological information to the scientific communities for analysis, assessment and mapping of the seismic risk of Bulgaria. The hardware and software are maintained at a high and up-to-date level to ensure reliable registration and processing of earthquakes on the territory of Bulgaria and surroundings in order to provide reliable information to the authorities and general public.

## AS25-0312

# Upgrading Indonesian Auxiliary Seismic Stations to Strengthen the CTBTO International Monitoring System

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Indonesia's auxiliary seismic stations are an essential component of the International Monitoring System (IMS), playing a critical role in the global efforts of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to detect and verify nuclear tests. These stations are located in important seismic regions and contribute valuable data to the IMS network. We are undertaking comprehensive upgrades at five key seismic stations: LEM, JAY, SIJI, PSI, and BATI. The upgrades aim to strengthen the monitoring system, enabling Indonesia to better fulfil its verification responsibilities and fully benefit from its participation in the CTBT regime.

Key improvements include upgrading the power systems to photovoltaic technology for increased autonomy and reliability in remote locations; transitioning from satellite (VSAT) to cellular (GSM) communication systems to reduce costs and enhance efficiency; modernizing to advanced digitizers for improved data precision and quality; implementing new Standard Station Interface (SSI) software and authentication systems to support data security and distribution; and receiving technical support from the CTBTO Provisional Technical Secretariat (PTS) for installation and operational training. Indonesia's Meteorology, Climatology, and Geophysical Agency (BMKG) has been actively participating in the planning of these works to ensure smoother future operation and maintenance.

These enhancements will significantly improve data accuracy, operational resilience, and transmission reliability, strengthening Indonesia's contribution to the IMS network. By supporting the CTBTO's nuclear test detection and verification capabilities, these upgrades reinforce global efforts in nuclear non-proliferation and disarmament under the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

## AS25-0324

# Automatic waveform-based amplitudes to compute the ISC MS and mb: an overview from over one year of data

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Starting with earthquake data month May 2022, we started to complement mb and MS parametric amplitudes reported to the International Seismological Centre (ISC, www.isc.ac.uk) from a multitude of agencies around the world with automatic measurements of amplitudes and periods from openly available waveforms. With this contribution we report on the results of the introduction in routine ISC operations of these automatic waveforms-based amplitude and period measurements for mb and MS computation, based on over one year of automatic waveforms processing. We highlight benefits of our updated computation procedure and outline both challenges encountered in the automatic processing and how we intend to best complement in the coming years the reported parametric data with our measurements.

## AS25-0352

# Integrated Microseismic Monitoring and Ground Deformation Analysis in Nisyros Island (SE Greece)

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Nisyros Island is situated in the eastern end of the South Aegean volcanic arc (Greece), a region that experiences the subduction of the African plate beneath the Eurasian, at a rate of ~30 mm/yr. The National and Kapodistrian University of Athens has installed seismological stations on the island to monitor its microseismicity, mainly focusing on the southern part. In this work, an analysis of the seismic activity recorded from September 2023 to March 2025, is conducted. More than 1,100 earthquakes were initially detected using advanced machine learning models, namely EQTransformer and GaMMA, alongside conventional methods. Refinement with HypoInverse software and an adapted local 1D velocity model resulted in a catalog of more than 800 earthquake events based on strict selection criteria. Microseismic activity is primarily located southwest of Nisyros, along a SW-NE fault zone that forms its southern basin, with few epicenters on the island itself, detected because of the dense local network and machine learning techniques. Ground deformation was monitored through continuous GNSS measurements from permanent stations on Nisyros, Kos, and Yali, processed utilizing precise satellite orbits and tidal models to determine daily station coordinates accurately. The area is subsiding at a rate of less than 10 mm/yr, which reduces towards the trench between Nisyros and Yali. This approach advances the understanding of microseismic activity and ground deformation, contributing to identifying key parameters for seismotectonic processes and emphasizing the importance of continuous monitoring in volcanic environments.

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## AS25-0385

# Paving the way for big data access and ML/AI seismological research in Aotearoa New Zealand

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Earth Sciences research is heading towards a future where artificial intelligence (AI) and machine learning (ML) play a key role. Both AI- and ML-led research projects require the availability and accessibility of multi-disciplinary, trustworthy big datasets, and global earth observation data centres are adapting. We will showcase three recent initiatives demonstrating how GeoNet (multi-hazard monitoring programme in Aotearoa New Zealand, led by GNS Science Te Pū Ao) is evolving its products and services to encourage and support modern research.

1. Improving our FAIRness. While FAIR supports broad data usage, it's also at the heart of making multi-disciplinary large datasets usable and machine-discoverable. We'll present FAIR scores from 2021 and 2024 and elucidate how findability and accessibility improvements (notably DOIs and launching TILDE, our multi-disciplinary data platform) support such usage.
2. GeoNet has been a partner in AWS Open Data Program since 2019. We are currently making 150 TB of data across our data domains available through that programme, supporting user-developed cloud-based solutions and processing GeoNet data in/near AWS. This ensures there are no limits on the data available via GeoNet.
3. AI and ML techniques require large, high-quality datasets for model training, testing and validation. We'll present a benchmarked dataset (hosted on AWS) comprising ~2.7M, 3-component waveforms and associated event metadata from the diverse GeoNet earthquake catalogue and data archive from 2013 to 2025. This is a novel and vital resource for both seismological research and developing novel AI models for operational seismology and evaluating existing models in the NZ context.

## AS25-0408

# Towards an FDSN standard for a PSD webservice

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We are considering proposing a new FDSN standard for a PSD (Power Spectral Density) web service. This web service will allow users to access PSDs, as well as PSD-derived spectrograms and PDFs (Probability Density Functions), computed from continuous seismic data. This project is supported by EIDA, EarthScope, and Geo-INQUIRE.

Noise level analyses utilizing PSDs are routinely used to characterize seismological station sites and perform data quality control. Moreover, seismic noise is now commonly used for tomography, monitoring the crust, and studying the coupling between the ocean and the solid Earth. Having an efficient way to retrieve or plot spectrograms and PDFs at a given site is useful for identifying which stations have recorded specific noise events (such as oceanic storms) and, more generally, for understanding the noise wavefield.

Nowadays, MUSTANG (EarthScope's quality metrics system) and SeedPSD (EIDA, under implementation) allow access to PSDs from stations whose data are hosted at Earthscope and at some EIDA nodes, respectively, but the services were developed with differences in usage and formats. We propose taking these efforts a step further by defining an FDSN web service standard that enables users to access all of these PSDs transparently, using standardized input and output parameters. In the longer term, this should facilitate the development of tools that query this web service to analyze and visualize PSDs and simplify access regardless of data center.

This poster describes the objectives and challenges of this project and discusses the technical choices considered.

## AS25-0412

# Exploring T-phases from earthquakes on the northern North-Atlantic mid-ocean ridge

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Seismological data from remote locations, such as those collected by ocean bottom seismographs (OBSs), can enrich and expand earthquake catalogues. OBS deployments not only enhance seismic monitoring e.g. along remote oceanic ridges, but also enable the development of advanced data processing techniques by integrating hydroacoustic and seismological approaches. In particular, T-phases offer valuable insights into offshore seismic events, creating an intersection between acoustic and seismological disciplines.

Here, we present methods for integrating P and T-phases recorded on hydrophones in earthquake detection and location. We exploit a local seismicity catalogue of the Arctic mid-ocean ridge, including 410 T-phases. During a one-year monitoring campaign (08.2018–08.2019) west of Svalbard, hydroacoustic and seismic data were collected continuously using three OBSs. This dataset is ideal for testing, as it includes both hydrophones and seismometers at the same OBS locations.

Our analysis reveals variations in the T-phase-generation, with more efficient excitation at the Mohns Ridge (MR) and Molloy Deep (MD). We examine the characteristics of T-phase events across different ridge segments, including their propagation time, duration, and frequency content. We will present preliminary results on earthquake localization using hydrophone data alone.

## AS25-0425

# A new cable-type seafloor observation network for earthquakes and tsunamis in the anticipated source area of the Nankai Trough earthquakes

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Observation of earthquakes and tsunamis that occur in the ocean in the vicinity of their source area is important both for academic and disaster mitigation purposes. The area from off Kochi to the Hyuga-nada, western Japan, which is the western half of the anticipated megathrust Nankai Trough earthquake source area, is a blank area of observation. To fill in the blank, NIED is constructing Nankai Trough Seafloor Observation Network for Earthquakes and Tsunami (N-net) (Aoi et al., UT2023). N-net consists of two subsystems, the offshore and inshore systems, each of which is equipped with 18 in-line observatories. Totally 36 observatories, which are positioned to cover the blank area as spatially homogeneous as possible, are connected by fiber-optic cables and installed on the seafloor. Each observatory is equipped with two sets of both strong-motion accelerometers and conventional velocity seismometers. For tsunami observation, each observatory is equipped with two newly-developed high-sensitivity MEMS-type pressure gauges. N-net is a hybrid system of an inline system and a node system, and is also equipped with a branching unit for future expandability. With the construction of N-net, earthquakes and tsunamis can be directly detected up to about 20 seconds and 20 minutes earlier, respectively. Construction of N-net is almost complete, and in addition to data from the offshore system, data from the inshore system is scheduled to be open to the public within 2025. In this presentation, we will introduce an overview of N-net as well as the observed data including the 2024 Hyuga-nada earthquake.

## AS25-0458

# Performance measurements of the New Zealand GeoNet seismological networks

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The Aotearoa New Zealand Geonet seismological networks operated by GNS Science Te Pū Ao produce a suite of earthquake themed products. These include earthquake catalogues, strong motion analysis records, as used within the engineering field, and shakemaps for event impact studies. These products are optimised to be generated soon after the earthquakes happen. However, over time there may be changes in the underlying data and meta-data which may introduce inconsistencies. This study is aimed at identifying, and ultimately correcting any such issues found. As well as highlighting the underlying causes, this becomes the first step towards building a mechanism to measure the performance of the networks.

The primary method used is to build a set of detectability curves based on the observed measurements and a knowledge of the underlying network geometry. For a set of earthquakes within defined depth and magnitude ranges, the observed values are compared to an ideal distribution, generated assuming all operational sensors have provided readings. The ratio of these summed values forms a detection curve for the given ranges. These can be compared to further data subsets, such as individual sites, sensor models, or quality metrics, which can then form the basis of operational reports on network performance.

The observed detection curves can also be used to model the future response of the network to possible earthquakes. For earthquake arrivals, for example, this forms the basis for estimating the network detectability and other related network design parameters and can be compared to theoretical detectability approaches.

## AS25-0462

# Earthquake early-warning alert in Israel due to a 370 T explosion in southern Lebanon, October 26th, 2024

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On October 26th, 2024, the Israeli Defence Forces (IDF) triggered an explosion of 370 T in an underground Hezbollah facility in southern Lebanon, ~1 km off the Israeli border, generating a seismic moment equivalent to a M3.6 earthquake. Four seconds after detonation, the Geological Survey of Israel's (GSI) Earthquake Early-Warning System, *Truaa*, identified the explosion as a M5.2 event, mislocating the epicentre by ~25 km. Since this exceeded *Truaa*'s warning threshold (M4.5), an alert was automatically sent by the IDF's Home Front Command systems up to an epicentral distance of 94 km. Seven seconds after detonation, the location and magnitude estimates were updated and stabilized to the actual location, and to a magnitude below the warning threshold.

We found that the *Truaa* system operated as designed and that the magnitude overestimation resulted from an unusually large explosion, short epicentral distances, and to mislocation due to a depth fixed at 8 km in *Truaa*'s location algorithm.

Real-time discrimination between earthquakes and explosions is still considered a research challenge not yet accomplished; it is a goal that is being explored in our research team. Similarly, the *Truaa* EEW system algorithm, *EPIC*, cannot discriminate between explosions and earthquakes. Therefore, we examined and tested several manual procedures, to prevent the alerting of such scheduled explosions. Some of these new measures are now part of the GSI's procedures.

As a result, we found no grounds to modify the operational configuration of *Truaa*.

## AS25-0485

# ORFEUS-Coordinated Seismological Datasets and Community Services

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ORFEUS (Observatories and Research Facilities for European Seismology, www.orfeus-eu.org) is a non-profit foundation that coordinates the collection, archival, and distribution of seismic waveform (meta)data, services and products based on international standards, and serves a broad community of seismological data users, on behalf of the Euro-Mediterranean seismic networks and monitoring agencies (orfeus.readthedocs.io/en/latest/governance.html). ORFEUS core domains comprise: (i) the European Integrated waveform Data Archive (EIDA; orfeus-eu.org/data/eida), providing access to raw seismic waveform data and basic station metadata; (ii) the European Strong-Motion databases (orfeus-eu.org/data/strong), offering automatically/manually processed waveforms, advanced station/site metadata, and associated products; iii) the European Mobile Instrument Pools (orfeus-eu.org/data/mobile), facilitating utilization of seismic instrumentation for temporary deployments. Currently, ORFEUS services distribute waveform data from about 31000 stations, including dense temporary experiments, emphasizing FAIR principles, open access, and high quality of datasets. ORFEUS services form a critical component of EPOS (www.epos-eu.org/tcs/seismology) and are seamlessly integrated into the EPOS Data Access Portal (www.ics-c.epos-eu.org). Access to data and products relies on state-of-the-art information and communication technologies, with a strong emphasis on web services for programmatic interaction. ORFEUS promotes the usage of transparent data policies and licenses and acknowledges the indispensable contribution of data providers. ORFEUS aims to enhance the existing services and facilitate access to massive & multidisciplinary datasets through collaborative efforts with global and regional initiatives, such as the FDSN and EarthScope, as well as support from EC-funded projects (e.g., www.geo-inquire.eu). ORFEUS also implements Community services that include software/travel grants, a vigorous training/outreach programme of webinars and workshops (www.orfeus-eu.org/other/workshops), and editorial initiatives.

## AS25-0516

# Improving FAIRness in the seismological community

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Decades before the FAIR principles were formally introduced (Wilkinson et al., 2016), the seismological community was among the first disciplines to make data freely accessible, using persistent identifiers for data attribution, and enhancing discoverability and interoperability. Seismology encouraged Open Data Policies and it became common practice to minimize embargo periods for datasets. Specifically, in 2014, the International Federation of Digital Seismograph Networks (FDSN) issued a public recommendation for members to mint DOIs for seismic networks, with updated recommendations released in December, 2023. The impacts of these recommendations were summarized by Pedersen et al. (2025, Seismica, accepted).

However, the rapid evolution of technologies like AI/ML and increasing capabilities of data discovery and processing at scale means that fully achieving FAIRness in data and metadata is a growing challenge. While seismological datasets are largely discoverable, accessible, and reusable within our community, and there are well-established standards for seismological waveform data exchange, challenges remain in making them "machine-actionable," a key principle of FAIR. StationXML metadata, though widely used, is not machine-actionable within a formal FAIR framework as it primarily contains in-situ, fixed content lacking external link references that could allow machines to interpret data sources and methods.

Significant work is underway to establish community-governed FAIR vocabularies in seismology. Emerging local implementations of vocabularies for passive seismic data (e.g., https://geofon.gfz-potsdam.de/cv/seisdata/) are being complemented by global discussions at the FDSN level to create unified standards.

In this work, we outline our roadmap for improving the FAIRness of seismological datasets.

## AS25-0535

# The Romanian National Seismic Network: Challenges and Perspectives in Earthquake Monitoring

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The Romanian National Seismic Network, operated by the National Institute for Earth Physics (NIEP), began its digital development in 2002. Over the years, continuous upgrades have enhanced the network's earthquake monitoring capabilities. The network is composed of digital seismic stations equipped with high-quality digitizers, broadband and short-period seismometers and accelerometers. Real-time data acquisition, processing, and analysis are performed using Antelope and SeisComp software which are running across two virtual machines, with one designated as the primary system and the other serving as a backup to ensure redundancy and reliability. An important factor is to evaluate the ambient seismic noise recorded by broadband seismic stations installed throughout Romania. The methodology is based on the analysis of the probability density functions (PDF) of the power spectral densities (PSD). With this method we can estimate the overall station quality and a baseline level of Earth noise at each site. Plots can be computed in real time and for different time periods using the algorithm implemented and continuously updated at NIEP. Additionally, NIEP contributes to the monitoring of critical infrastructures and important buildings by collecting and analyzing data from accelerometers, enhancing the understanding of structural response during seismic events. Through continuous development and integration of advanced tools and technologies, the Romanian National Seismic Network plays a pivotal role in seismic hazard assessment and risk mitigation. By ensuring high-quality data acquisition, processing, and analysis and by expanding its monitoring capabilities to include critical infrastructures, NIEP significantly contributes to both scientific research and public safety.

## AS25-0544

# DOI, licence and citation uptake for seismological waveform data: 10 years evaluation and future actions

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In 2014, FDSN recommended using DataCite Digital Object Identifiers (DOIs) for seismic networks to enhance data attribution, citation, and impact metrics. This study evaluates the level of adoption of DOIs and licenses across FDSN-registered networks, analyzing their influence on data citation and compliance with FAIR (Findability, Accessibility, Interoperability, and Reusability) principles which were first published in 2016.

73% of seismic networks have adopted DOIs, with more than 80% DOI coverage for networks created after 2014. Licensing adoption, not covered by present FDSN recommendations but recommended by the FAIR principles, remains low (8%), with significant regional variations. The main challenges presently are barriers to systematic data citation, whether on the scientist or publisher side. Citations have increased substantially, but improvements are needed to support and implement correct data citation across all levels, including networks, data centers, scientists and journals. This work highlights best practices and provides a set of recommendations for improving attribution, citation, and FAIRness of seismological waveform data. These insights aim to guide future FDSN strategies and better align seismological waveform data with the FAIR principles, and in particular, enable machine-actionability. An added value of the assessment was that many minor errors and inconsistencies were identified and fixed at FDSN and in the seismological metadata. This work is carried through a collaboration involving 7 organisations worldwide, and with close ties to FDSN. It contributes to the Geo-INQUIRE project workprogramme.

## AS25-0553

# The Advancement of OVSICORI-UNA's Seismic and Volcanic Monitoring Network in Costa Rica

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Since approximately 2006, the geophysical monitoring network of OVSICORI-UNA has undergone significant advancements, driven by the transition from analog to digital technology. Starting in 2007, with financial support from the National Emergency and Risk Prevention Law, the replacement of analog seismic equipment with digital Q330 devices and STS-2 sensors began. This support from the Government of Costa Rica has been crucial in strengthening geophysical monitoring networks across the country.

Between 2007 and 2025, OVSICORI's network has grown significantly, covering various remote monitoring areas such as geochemistry, gas monitoring, volcanic and tectonic seismic monitoring, and the implementation of volcanic video surveillance systems. By 2025, the network consists of approximately 200 stations equipped with different geophysical monitoring techniques.

Additionally, since 2007, the OVSICORI data center has been expanded to store all digital remote monitoring records. Currently, this data center is located at the OVSICORI facilities and features a mirrored system at the UNA Network Center, ensuring the security and availability of information.

Another significant advancement has been the implementation of an early warning system for seismic events in Costa Rica, contributing to risk mitigation. Thanks to OVSICORI's current geophysical monitoring infrastructure, a vast amount of valuable data is generated for scientific research and the protection of the population against seismic and volcanic events.

## AS25-0578

# The European-Mediterranean Seismological Center (EMSC) and LastQuake, its rapid information and crowdsourcing system

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The EMSC is a non-profit NGO providing rapid public information on earthquakes on a global scale through its multi-component LastQuake system. The purpose of this presentation is to introduce its role, how its services work and how they fit with those of national agencies, and how earthquake networks can contribute to and benefit from these services.

The EMSC aggregates the parametric data shared by 113 networks, allowing it to provide global earthquake information as a supplemental and back-up service to national and regional agencies. Information about the effects of earthquakes is crowdsourced from eyewitnesses through the LastQuake system, which consists of websites, a Telegram and Twitter bot, and a smartphone app, that uses a system of cartoons depicting the 12 levels of the macroseismic scale rather than the classic questionnaire. Felt earthquakes are automatically identified by crowdsourced detection, i.e. by detecting the online information-seeking behaviour of eyewitnesses within a dozen of seconds of an earthquake. The automatic publication of these crowdsourced detections on the LastQuake system 15 to 90s after the quake initiates a massive collection of eyewitness reports. For example, 5,000 felt reports were collected in the 30 minutes following the dramatic earthquake in Turkey in February 2023. Furthermore, the combined analysis of crowdsourced detections and seismic data – via a method called CsLoc – provides fast (~100s) and reliable (~10 km accuracy) seismic locations of felt earthquakes at global scale. Beyond these services, we will also show how LastQuake improves awareness and supports crisis communication, as well as fights against misinformation.

## AS25-0601

# Truaa: three years of operational experience with Israel's earthquake early warning system

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The Israeli national earthquake early warning (EEW) system, Truaa, has been operational since January 27, 2022. The system is based upon 116 stations within the Israeli Seismic Network (ISN) operated by the Geological Survey of Israel (GSI). Truaa's operations are monitored 24/7 by the GSI's Emergency Operations Center (EOC), which provides first response and support to stakeholders. Since becoming operational, Truaa has identified all local felt earthquakes, and no false alerts have been issued, though some teleseismic events were initially misclassified as local earthquakes.

On October 26th, 2024, Truaa disseminated an EEW to over a million people following the identification of a scheduled 370-ton explosion set by the Israeli Defence Forces (IDF) as a M5.2 earthquake. While this was not a natural earthquake, the event highlighted the need to consider anthropogenic seismic sources in EEW system design and algorithms, demonstrated Truaa's end-to-end capabilities, and allowed the GSI team to perform under a real scenario conditions.

We will present the current operational aspects of Truaa and the Israel ISN, data-sharing policies, and strategies to mitigate teleseismic and anthropogenic events in the context of EEWS in a low-seismicity region.

## AS25-0613

# Azimuthal Information Criteria For Screening GT5 Events

*Keith Mclaughlin*[1]

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Gallacher et al. (2025) propose refinement of the Bondar and McLaughlin (2009) GT5 criteria used to screen events for nomination to the ISC GT5 list. They augment the previous DU criteria with a more robust Cyclic Polygon Quotient (CPQ) criteria based on the station azimuthal sampling. This work examines CPQ and DU in light of a measure of the information sampled by the azimuthal distribution of stations vector **A**= [$az_1$, $az_2$, …, $az_N$], where $az_j$ <= $az_{j+1}$. CPQ is a function of the vector, **D** = [$az_2$-$az_1$, $az_3$-$az_2$, …, $az_1$+2p -$az_N$]/2p. CPQ(**D**) is demonstrated to have a statistical logarithmic relationship to a formulation of the Empirical Shannon Information we define as ESI(**D**) = $S_{j=1,N}$ -$D_j$ $\log_2(D_j)$. The maximum possible CPQ for N stations is a uniform azimuthal distribution with spacing $D_j$ = 2p/N radians. This uniform distribution of N stations corresponds to a maximum value ESI = $\log_2$(N) bits. ESI(**D**) may be a useful intuitive measure of the potential information content of the station azimuthal distribution, **D**. Examples are presented and Monte Carlo simulations explore these relationships. CPQ(**D**) is shown to better correlate with ESI(**D**) than DU(**D**) and hence better reflects the information content. This analysis supports using CPQ criteria in screening event locations for GT5 and contributes to an intuitive understanding of sufficiently balanced network azimuthal distributions, **D**, to assure unbiased epicentral locations.

## AS25-0614

# Mb Magnitude Station-Station Spatial Correlations and Regional Station mb Biases

*Keith Mclaughlin*[1]

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Station mb's from ISC (2000–2020) and NEIC (2017–2021) catalogs are examined for station effects (station amplitude biases). Analyses include a General Linear Model (GLM) as well as statistics of station residuals w.r.t. the network average. Residuals were examined versus epicentral distance, network magnitude and with time. Consistent station biases are observed in both catalogs with regional spatial correlation and consistent over time. That is, most stations systematically report a magnitude higher or lower w.r.t. the network average. A global statistical station-station covariance structure may be extracted from the residuals. That is, mb's reported by two stations within 100 km will generally be correlated, consistent with Yeck et al. (2024). While the mb network standard deviation is generally 0.35–0.40 units, two stations less than 100 km apart will likely report inter station differences 50% of the global distribution. Station biases for most sites are remarkably stable over time with events from multiple source regions. These observations support the use of a full model covariance matrix while estimating network mb. Station biases exhibit spatial patterns that correlate with geophysical/tectonic provinces and contain valuable geophysical information. Preliminary analysis shows correlations with published upper mantle and upper crustal velocities suggesting near surface impedance signatures are superimposed on signatures of upper mantle attenuation.

## AS25-0640

# Embedding a Local-Scale Seismic Network into a Regional-Scale Seismic Network

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The University of Utah Seismograph Stations (UUSS) is authoritative for monitoring seismicity in the Utah Region and Yellowstone National Park, U.S.. In 2019, UUSS began building out a local-scale seismic network, incorporating this data into regional operations to monitor the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) project. In general, the regional- and local-scale networks have the same goals—detect, locate, and provide magnitudes for earthquakes within the regions of interest. In practice, implementing the tools and procedures to meet these goals is different. At the regional-scale, the UUSS network is composed of a mix of surface broadband, short-period, and accelerometer stations distributed across the state. Earthquake rates are typically tens of earthquakes per month with a general M*comp* around ML 1.5. At the Utah FORGE site, the network is composed of a spatially dense network with a mix of nine broadband and accelerometer stations located at the surface, six shallow (30–40 m) instrumented boreholes and one 300 m instrumented borehole. During operations earthquake rates can exceed several hundred events per hour. The general M*comp* is around ML -1.0. While it was initially convenient to integrate data flows and processing from the two networks, we have learned that it is not optimal to have a single system meet both goals. In this study, we describe lessons learned regarding incorporating different sampling rates, tuning triggering algorithms, issues with calculating local magnitudes, and implementing a separate processing system for monitoring the smaller magnitude events.

## AS25-0693

# Increase the information content of the regional earthquake bulletin in North Caucasus region by implementation ML and Mw magnitudes

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The North Caucasus is characterized by the highest seismic activity in European Russia. Seismic activity in North Caucasus is routinely monitored by the seismic network of Geophysical Survey, Russian Academy of Sciences, which is registered in the FDSN with network code RU. The goal of the work was to increase the information content of the regional earthquake catalogue in this region by calculating local and moment magnitudes. The most common estimate of the earthquake size in the Caucasus region was energy classes Kp of T.G. Rautian. A calibration function for calculating the local magnitude ML were obtained, which includes regional features of attenuation and geometrical spreading with distance and local soil amplification at the seismic station location. To calculate the moment magnitude using the spectral method, we estimated the attenuation of seismic waves in the region using the quality factor of the medium Qc(f). To do this, we explored the coda-waves attenuation properties of this region by applying the single back scattering model to local earthquakes recorded in the area in the period 2013–2021. We used average values of the Qc(f) for attenuation correction in the observed S-wave spectrum for the correct calculation of source spectra and obtained the average value of the seismic moment $M_0$ and moment magnitude $M_w$. A detailed study of intermagnitude relationships was carried out.

## AS25-0695

# Earthquake monitoring in central Mediterranean area: the Malta seismic network

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The Malta Seismic Network (MSN, https://doi.org/10.7914/SN/ML), managed by the Seismic Monitoring and Research Group within the Department of Geosciences at the University of Malta (http://seismic.research.um.edu.mt), serves as the nation's primary facility for monitoring and studying seismic activity around the Maltese Islands. Established to enhance the detection and analysis of earthquakes in the region, the MSN has evolved significantly since its inception. The network currently comprises nine permanent broadband seismic stations strategically distributed across the archipelago. The oldest station, located at Wied Dalam (WDD), was installed in 1995 as part of MEDNET—a Mediterranean-wide network managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome—aiming to improve the understanding of the region's seismic dynamics. In 2003, WDD was upgraded to an online system, enabling real-time data transmission. The primary objective of the MSN is to monitor seismicity in real-time and to accurately locate earthquakes occurring near the Maltese Islands and within the Sicily Channel. This area exhibits complex tectonic processes resulting from the collision between the African and Eurasian plates. The dense network not only improves the localization of seismic events but also provides valuable data on microearthquake activity, which was challenging to study in the past. Additionally, the network facilitates analyses contributing to comprehensive seismic hazard assessments. We present the latest developments in earthquake and tsunami monitoring and network advancements. Furthermore, we discuss the use of the recent ten portable quasi-broadband stations and fifteen short-period instruments available for site response and building investigations or temporary experiments.

## AS25-0727

# GOK-Net: A temporary seismic network in Gulf of Gökova, Western Türkiye

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The Gulf of Gökova is one of the most seismically active regions in Türkiye, located within the Western Anatolian horst and graben system, part of the Aegean subduction zone. The region has experienced significant seismic activity throughout both historical and instrumental periods, including the 2017 Mw 6.6 Bodrum earthquake and recent seismic activity near Santorini, drawing considerable scientific interest.

To enhance microearthquake detection, better understand the characteristics of the earthquakes and gain deeper insight into the interaction between the surface faults and deeper structures, a temporary network of nine broadband seismometers operated from 2021 to 2023. In this study, we assess the ambient noise levels at each station and examine seasonal variations. P- and S-wave phases are manually picked, and quarry blasts are identified. Hypocenters are located using NonLinLoc, and improvements in microearthquake detection are evaluated in comparison to existing earthquake catalogs from local networks. Our findings provide a more detailed seismic characterization of the Gulf of Gökova and offer valuable insights into its tectonic activity.

## AS25-0816

# Enhancing the IG-NOA (ATH) Seismic Catalogue (2004–2024): Adding teleseismic readings and updating local events parameters

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Since 2007, IG-NOA has been collecting data and locating earthquakes using the Hellenic Unified Seismic Network (H.U.S.N.). Recently, efforts have been made to update, enhance, and standardize the parametric database for improved consistency and completeness. This process has involved two key components: Completing teleseismic readings since 2011, when IG-NOA stopped reading teleseismic data, and reviewing and homogenizing the parametric local earthquake database to ensure consistency and accuracy.

Teleseismic data from 815 global events with mb ≥ 6 between 2011 and 2021 have been thoroughly analysed to extract as many phase and amplitude readings as possible. The results indicate a significant increase in observations compared to other agencies reports submitted to International Seismological Centre (ISC), particularly depth-type phases, S-type phases, and amplitudes used in broadband magnitudes. A comparison of broadband NOA MS to ISC Ms reveals a nearly 1:1 relationship. Therefore, it is recommended to use NOA MS instead of Ms to avoid the challenge of reading amplitudes in the 18–22 s period range.

Data for local earthquakes are available at https://bbnet.gein.noa.gr/HL/ in two different non-standard formats. These were converted to Nordic format, as used in SEISAN, to establish a standardized format. During this conversion process, numerous errors and inconsistencies were corrected, the most significant being a factor-of-2 error in amplitudes (peak to peak instead of zero to peak) between February 2011 and December 2019.

Tests have been made to verify the magnitudes consistency and accuracy. Statistical data analysis will be presented, with a particular focus on evaluating magnitudes accuracy.

## AS25-0856

# The Permanent Seismic Observation System in Chile

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Chile is among the most seismically active countries in the world. Not only in terms of the high frequency of events, but also for the large extent they can reach and the tsunamis they can generate. Since 1900, more than ten events with a magnitude around 8 or larger have taken place in this region, including several with magnitudes close to 9 and above. Such extreme seismic activity is the result of the interaction of the Nazca, Antarctic, Scotia, and South American plates, where Chile is located.

Fifteen years have passed since the M8.8 Maule earthquake, event that catalyzed the installation of a real-time digital broadband/strong-motion/GNSS network, designed to provide fast and accurate estimates of earthquake source parameters of potentially devastating earthquakes for emergency response applications and capable of comprehensive characterization of Chilean seismicity, necessary for long-term hazard assessment and mitigation activities.

New developments, such as the production of real-time instrumental intensity maps, Shakemaps, W-Phase estimated moment tensors, GNSS corrected acceleration streams, coda magnitude estimation, and results of the first tests of DAS submarine fiber will be presented. Additionally, authorities have charged CSN with the preparation of seismic hazards maps, of which the first version will be available at the end of the year.

Since the installation of this network, broadband data in real time have been publicly available through Earthscope´s Data Management Center, under networks C and C1. Strong-motion data for recorded accelerations exceeding 2%g as well as daily GNSS data are available through the CSN webpage.

## AS25-0860

# Revising the seismic ground truth reference event identification criteria

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Well constrained seismic event locations are identified and added to the IASPEI Reference Events List (referred to as the GT List) by evaluating events reported in the International Seismological Centre (ISC) Bulletin. The criteria used for identifying events to be added to the GT List were proposed by Bondár and McLaughlin (2009) and include a measure of the azimuthal distribution of stations within 150 km of the event. We test these criteria by relocating known explosions using the ISC location algorithm, which accounts for unbalanced azimuthal station distributions, and show that there is no need to exclude events from the GT List based on uneven azimuthal station distribution. We therefore propose a revised set of criteria for identifying GT events, including a less exclusive measure of azimuthal station coverage defined as the Cyclic Polygon Quotient (CPQ). CPQ is the ratio of the area of a cyclic polygon formed by connecting event to station azimuths on a unitary circle, and the area of the unitary circle. Furthermore, we extend the selection criteria for depth resolution to allow the depth to be constrained by either a close-by station or multiple stations reporting both P and S phases. Using these criteria, we show an increase in the number of events in the GT list from ~10,000 events to greater than 70,000 events and demonstrate that there is no measurable reduction in location accuracy. This updated criteria results in greater geographic coverage of events added to the GT list.

## AS25-0863

# Station statistics from data reported to the International Seismological Centre

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The International Seismological Centre (ISC) has received phase picks from a total of 596 agencies over its entire period of operations, from 1959 – present, with stations distributed throughout the globe. The approximately 20 million phases reported to the ISC yearly in the modern era, including phases reported to the ISC by multiple agencies at the same stations, form the perfect dataset to evaluate the performance of stations over time. One of the many metrics used to evaluate station performance is the change in the station phase residuals over time. Additionally if a station is mislocated this will result in a characteristic pattern in the phase residual sorted by station to event azimuth which can be detected automatically. Another instructive metric for identifying issues at a reporting station is the deviation in reported S-P arrival time from the predicted S-P arrival time. These can be automatically detected by identifying station with increasing S-P arrival time deviation with distance. Further by comparing reported station magnitudes to the Event magnitude it is possible to identify whether a station is overestimating or underestimating the magnitude of events. When this discrepancy is above a threshold the station can be automatically identified for further investigation. We will show examples of stations exhibiting these features and detail how the ISC automatically identifies and attempts to address these issues. Additionally all ISC station statistics are available through the ISC website.

## AS25-0871

# Local magnitude (ML) calibration in the short-distance range using the dense Collalto network and surrounding seismic stations in northeastern Italy

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The accurate estimation of local magnitude (ML) at short distances is critical for monitoring the seismic source processes and detecting potential induced seismicity in industrial underground activities. This study calibrates a parametric local magnitude scale for northeastern Italy, centered on the Collalto seismic network, using the IASPEI-recommended formulation and a modified data-driven approach. We analyze digital data (2012–2023) from the Collalto network and regional stations, deriving Wood-Anderson amplitudes from full waveforms, and using ad-hoc developed pre- and post-processing techniques. The final dataset includes nearly 30,000 horizontal and 22,000 vertical observations, covering distances from 5 to 250 km and magnitudes from microearthquakes (ML<0.0) to moderate events (ML=5.9). Initial inversions reveal anomalous coefficient values, likely biased by an uneven data distribution across distance ranges. We then introduce a Monte Carlo subsampling procedure to extract uniformly distributed subsets, and derive final equations for horizontal and vertical components. Our ML scale is consistent with commonly used equations up to 200 km, with maximum differences ≤0.3 magnitude units. Average residuals reveal a ±0.1 perturbation between 30 and 200 km, closely matching attenuation anomalies reckoned by other authors too, and interpreted as effects of the Moho discontinuity on Wood-Anderson amplitudes. Static station coefficients are calculated for each change in sensor configuration; they are coherent with site geology and sensor placement (e.g. borehole versus surface deployment). This calibration law is well constrained at short distances, and remains reliable at regional scale, and in a wide magnitude range, making it applicable to both coexisting local and regional networks in northeastern Italy.

## AS25-0878

# Status of Seismic Station Network and Automated Quality Control of Korea Meteorological Administration(KMA)

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The Korea Meteorological Administration (KMA) is the primary agency responsible for the national earthquake response system, including establishing and operating seismic stations, and monitoring, analyzing, and issuing warnings. Currently, the KMA operates 371 seismic stations and collects real-time data from 650 stations affiliated with relevant domestic organizations, incorporating 120 stations that meet stringent quality criteria into the national seismic monitoring network. Based on this data, the KMA provides real-time information such as the epicenter, magnitude, and intensity of earthquakes and issues early earthquake warnings for significant events to facilitate rapid disaster response. To improve early earthquake warnings, minimizing the time for each stage—detection (from four stations), data collection, transmission, analysis, and notification—is essential. Since reducing time in stages other than detection has reached the limits of current technology, increasing the density of the seismic station network is necessary. The KMA plans to establish 160 new accelerometer seismic stations, installing 40 annually from 2024 to 2027, and expand the use of seismic stations from relevant domestic organizations. The quality of seismic data is crucial to preventing erroneous analyses, delays, and missed detections. As the number of seismic stations increases, effective quality management becomes more challenging. To address this, the KMA implemented an automatic quality management system in 2019 to improve efficiency and ensure systematic quality control. This system includes five key performance indicators for seismic data. The quality analysis is disseminated through both the quality management system and the National Earthquake Comprehensive Information System (NECIS) in real time.

## AS25-0919

# Recent evolutions of the GEOSCOPE global network

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The GEOSCOPE observatory provides more than four decades of high-quality continuous broadband data to the scientific community. Started in 1982 with a few stations, the network has grown over the years thanks to numerous international partnerships. The 34 operational GEOSCOPE stations are installed in 18 countries, filling gaps in the global Earth coverage (in Africa, Antarctica, Indian Ocean, Pacific Ocean islands and more). The stations are equipped with the best quality seismometers (from the very first STS1 in the early 80's to the last Trilium T360 nowadays) and digitizers (Q330HR and Centaur), in order to record with a high fidelity the ground motions generated by all types of seismic sources. Furthermore, a number of stations are also equipped with accelerometers, pressure and temperature sensors allowing for a wider range of observable events such as the 2022 Hunga-Tonga eruption. All the data (real-time and consolidated archives) are publicly available at the IPGP, Earthscope and Epos-France data centers using standard protocols. After reviewing the current state of the network, we will focus on its recent evolutions, and in particular on the increasing number of new generation broadband sensors now installed in caves or in (deep) boreholes. Examples from the new MATO station (western Brazil, operational since November 2024) and from the recent installation developments in Antarctica (CCD station on the Concordia base) will be specifically documented.

## AS25-0931

# Site conditions for seismic stations in the region of Eastern Macedonia and Thrace

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Characterizing station conditions is important for any network. Is it often implicitly assumed for broadband/seismological and strong-motion rock stations that reference conditions apply, but this is questionable. There are few studies to characterise Greek stations. Within EU project COREu that focuses on seismicity and hazard in the area of Kavala, stations in Macedonia and Thrace hold particular interest, so for each station we: 1. compile available metadata such as geology, topography, installation conditions, Vs30; 2. study standard geological maps to characterize geological unit and age; 3. elicit information directly from the network operators from in-person site visits; 4. analyse waveforms to estimate local site amplification using the horizontal-to-vertical spectral ratio (HVSR) technique and assess its sensitivity. To achieve the latter, we must first perform strict QA and processing in the time and frequency domain to curate a tailored dataset. We then co-assess the parameters derived from all aforementioned steps to evaluate each station's overall capacity as a reference site. In addition to the study of the permanent network stations, we also consider their layout and available geological and geotechnical information in the vicinity of Kavala in order to select additional locations for installing new stations for local monitoring purposes. This work intends to inform the study of background seismicity and seismic hazard within the COREU project in the Kavala area.

## AS25-0964

# Monitoring time variations in seismic noise amplitude at permanent seismic networks

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The quality control process usually followed at broad-band seismic networks includes the calculation of the power spectral density and their probability density functions. However, these results do not make possible a quick estimation of temporal variations that can result from non-continuous sources of noise such as meteorologic phenomena or human activity.

We propose the use of the SeismoRMS package, originally developed to analyze the seismic amplitude variations associated with the COVID19 lockdown, to monitor the time evolution of seismic noise sources in a permanent network, using as a case study the dataset collected during 2023 by the CA network in NE Iberia.

Frequencies above 1 Hz show remarkable differences between the stations, despite sharing similar installation settings. Most of the sites show diurnal and working days/week-end variations, suggesting a relevant contribution of anthropogenic sources, but the amplitude of such variations differs strongly among the sites. Our study allows us to identify specific noise sources affecting some sites during short and regular time periods, an aspect that need to be taken into account when evaluating the overall quality of each site. We conclude that a systematic analysis of the amplitude variations at different frequency bands can be a tool of interest for the management of a broad-band seismic network.

This work has benefited from the use of the GEO3BCN-CSIC LabSis equipment and from partial support of the EPYSIM Project, funded by the Spanish Ministry of Science and Innovation (Ref.: PID2022-136981NB-I00).

## AS25-1027

# Advances in signal processing techniques for discrimination of quarry explosions from seismic activity

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In recent years, the monitoring of explosions has become increasingly important, both from an environmental and safety perspective. The detection and analysis of these explosions involve sophisticated signal processing techniques, which have evolved significantly to enhance accuracy and efficiency.

In this study, we will analyze explosions from quarries in Romania using data from the Romanian National Seismic Network. As test case we are presenting the study on wave forms from seismic stations (e.g. CPSR, PTSR, LERL, DBRR, and GZR) that recorded the ground motion near the quarry Suseni, Gorj County, Romania. Other examples of explosions will also be presented.

Multiple waveforms have been registered using digital seismic equipment in order to train a model capable to discriminate between natural seismic phenomena and artificial ones i.e. explosions. All waveforms were pre-processed using a number of techniques including: segmentation, interpolation, conventional and adaptive filtering, and signal peak and envelope extraction. The database was then divided in two datasets: one dataset used to train and another dataset used to test a supervised machine learning model. Multiple models were trained and compared. Their purpose was to classify an earthquake or explosion with an accuracy exceeding 90%.

## AS25-1101

# Machine-Learning Advancements in Operational Earthquake Monitoring at Local and Regional Scales—as Demonstrated in Switzerland

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Machine learning (ML) is now in widespread use in seismology, and has been demonstrated to dramatically improve earthquake catalogues, though it is rarely applied in operational real time monitoring. The Swiss seismic network has now grown to include over 400 real time stations, and currently detects over 2000 events per year that are each manually characterised—an increasingly-high workload. In this presentation we will show how various ML tools are progressively being integrated into the real time national monitoring at the SED, allowing us to deepen the completeness and improve the accuracy of our catalogue, as well as reduce the effort of manual review. We focus on implementation within the standard monitoring software SeisComP we operate so we can leverage all the benefits of the existing mature monitoring framework. The scdlpicker SeisComP module (Tillman et al., 2023) creates an interface between SeisComP and the trained ML pickers in SeisBench (Woollam et al., 2022) to allow event-based re-picking (i.e., not real-time phase onset detection) for both P and S picks at local distances, and add pick uncertainty and P-pick first motion polarity. Further, we show how de-noising waveforms can lead to deeper catalogues with enhanced location and magnitude precision. We demonstrate the performance of these extended features in the routine earthquake monitoring at the Swiss Seismological Service (SED).

## AS25-1104

# Summary of the Bulletin of the ISC: individual network's history, current status and procedures

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Approximately every six months, the ISC publishes a periodical book called the Summary of the Bulletin of the ISC. At first, the book is distributed to ISC Member-Institutions, national public libraries, and a few customers. Soon after that it becomes freely and openly available on-line.

Primarily, the book is designed to give an overview of every six months of ISC data as well as to describe ISC mission, routine procedures, standards, and formats used to produce and distribute the Bulletin. The Bulletin integrates parametric seismic event data (catalogues) routinely reported to ISC by ~150 seismic networks and data centres worldwide of which ~60 are in Europe and Mediterranean region, ~40—in Asia, and ~25—in Americas. Parameters of these individual data contributions to ISC are also described in the book.

In addition, the book incorporates invited articles from contributing seismic networks. These articles describe the history, current status, and procedures used by these networks to determine the location of seismic events, magnitudes, source parameters, event types, etc. These articles are reviewed at ISC by the Summary Editor, DOI assigned via CrossRef, and the articles are published as part of the Summary at no cost to the authors.

So far, we published such articles from a total of 19 networks. The articles are accessible via relevant agencies in the ISC Agency Registry and their hypocentre solutions in the Bulletin. We invite network operators, collaborating with us, to contribute their articles for publication in the Summary.

## AS25-1120

# Comparing broadband and strong-motion data using collocated sensors in Greece

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Good quality seismic data is of great importance in a wide range of seismological studies, whether focusing on the source, path or site effect. Errors related to the sensors (calibration, orientation, or installation issues) or metadata may produce unreliable data, either in all or in part of the frequency range of interest.

In this study, we focus our attention on selected stations of the Hellenic Unified Seismic Network (HUSN), and in particular on the two networks that possess co-located broadband and strong motion sensors (National Observatory of Athens and University of Patras, respectively), with a view to scrutinizing their data over their frequency band and time period of common operation.

We compiled a dataset of more than 2500 recordings from a total of 35 collocated sensors. Our records are of events with magnitudes M4 or larger, at distances depending on magnitude. After inspecting the raw waveforms, we manually process them in the time and frequency domain. By examining cases where differences occurred, we identified certain errors in sensor response. We determined the usable frequency range on a waveform-specific basis and compared this range between the respective channels. Considering the noise regime per station, we assessed the reliability and usability of data at the low and high end of the usable frequency range of the acceleration spectrum.

This work will enhance the data quality, reduce uncertainties within the COREU project in Kavala region. Also, it will have impact in research related to event location, tomographic studies, source analysis, strong-motion applications and shakemaps.

## AS25-1181

# SISMIKO Response to the 2024 Pietrapaola Seismic Swarm in the Calabrian Upper Ionian Side

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On August 1, 2024, at 21:43 local time (19:43 UTC), a MW 5.0 earthquake struck near Pietrapaola (Cosenza), Calabrian Upper Ionian side, approximately 10 km inland from the coast. The geodynamic evolution of this area is influenced by the subduction of the Ionian slab and the back-arc spreading in the Tyrrhenian Sea, driven by the convergence of the Africa and Eurasia plates. Historical seismicity includes significant earthquakes exceeding MW 6.5, such as those of 1638 and 1836, emphasizing the region's high seismogenic potential.

Following the mainshock, the SISMIKO, INGVtask force, quickly deployed a temporary seismic network (FDSN code 3Q) to improve the geometry of the permanent networks, enhance event location accuracy, and reduce azimuthal gaps. Within two days, three seismic stations were installed and integrated into the INGV monitoring system, with a fourth station added later to replace a temporarily decommissioned permanent site. The data were made available in real-time through EIDA for scientific analysis and seismic surveillance.

In mid-August, a second swarm occurred near Cirò (Crotone), where over 200 events had been recorded since May, including two MW 4.0. This provided an opportunity to test a localization system which implements a deep-neural-network-based algorithm (PhaseNet) for automatic phase picking. Preliminary results suggest that the completeness magnitude threshold seems to decrease when compared to the INGV catalogue, with an increase in detected events, depending on system settings. This study emphasizes the crucial role of regional seismic networks in emergency response and their potential integration with real-time machine learning-based detection methods.

## AS25-1214

# Towards archiving, distributing and using large seismological datasets

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As an observational science, seismology strongly profits from international data standards and protocols, which greatly facilitate data exchange and collaboration. Currently, seismological data centers are facing a new challenge of big data ingestion and distribution. Rapid expansion of conventional archives due to network densification, increased archival and distribution, and large temporary deployments are even surpassed by the influx of massive datasets from new types of instrumentation. New infrastructure is needed for the archival and distribution of large-N deployments of seismic nodes and, in particular, fiber optic sensing such as distributed acoustic sensing (DAS) and related techniques like distributed strain sensing. One of the goals of the Geo-Inquire project is to build up and enable the usage of this infrastructure. Moreover, the Findable, Accessible, Interoperable and Reusable (FAIR) management of these types of data requires a coordinated effort from the international seismological community.

Recent efforts in using object storage to manage and exploit DAS datasets yield promising results. In this contribution, we will show test cases for the management of big seismological data e.g. from seismic nodes in S3-compatible object storage and array database management systems such as TileDB. We will highlight challenges and opportunities from the perspective of data centers, e.g. in providing asynchronous data download, as well as from the perspective of potential users, e.g. in adapting established workflows to new formats. We aim to initiate a discussion with future users to pave the way towards adoption in scientific workflows and experiments.

## AS25-1305

# Advancing seismological research through Geo-INQUIRE: enhanced data access, workflows, data lakes, transnational access and trainings

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The EU-funded Geo-INQUIRE (Geosphere INfrastructures for QUestions into Integrated REsearch) project, running from 10.2022 to 09.2026, aims to improve access to key geoscientific data, products and services. By integrating and improving data infrastructures, Geo-INQUIRE facilitates high-resolution monitoring and modeling of dynamic processes in the geosphere.

In the field of seismology, Geo-INQUIRE plays a key role in enhancing virtual access (VA) to extensive seismological waveform data through the European Integrated Data Archive (EIDA). EIDA is a distributed federation of data centers that securely archives seismic waveform data and metadata collected by European research infrastructures. During the project, new data centers and holdings are added and new data types are integrated, such as DAS and SMART cable sensors, as well as other ocean-related observables.

In addition, Geo-INQUIRE provides Transnational Access (TA) to selected testbeds from key facilities and High-Performance Computing (HPC) resources, enabling researchers to perform advanced simulations of seismic waves, rupture dynamics, and related geohazards. A large number of trainings, summer schools, workshops and seminars are organized to facilitate the adoption of an open science culture in the community and to accelerate the adoption of new services and data.

Ultimately, this initiative supports multidisciplinary research, fosters cross-fertilization between infrastructures beyond seismology and Earth physics, and contributes to the advancement of seismological research and a deeper understanding of our complex and dynamic planet.

## AS25-1376

# On the importance of properly documenting and disseminating information on the installation conditions of seismological stations through earthquake data centers

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Accurate recordings of ground motion, as provided by earthquake data centers, are essential for the reliable assessment of seismicity and seismic hazard. However, the current databases used to develop ground motion models (GMM) or to establish seismicity catalogs rarely provide detailed information on the installation conditions of the sensors, often considering them as free-field measurements. However, in reality, the sensors are installed according to a wide variety of methods specific to each seismological network, and these conditions significantly influence the recorded signals (amplification or deamplification depending on the frequency).

Through case studies, we will analyze the impact of the different installation configurations on the seismic recordings, highlighting the differences from a true free field. In particular, we will examine: 1/ the effect of installation depth (postholes, manholes, tunnels), 2/ soil-structure interaction (sensors installed in the foundation slabs or basements of buildings), 3/ the influence of specific supports (slabs, seismic pillars) and 4/ the effects of short-wavelength topography.

We will show that disregarding these factors can introduce bias in the development of GMMs or the estimation of magnitudes. We will thus emphasize the need for earthquake data centers and seismological networks to better document these installation conditions in database metadata, in order to guarantee a more rigorous use of the recordings. Finally, we will propose the development of a best practice guide, in consultation with data managers, for the installation of seismological stations. This would improve the quality of stored and shared seismic data and limit the impact of external disturbances on recordings.

## AS25-1379

# Introduction to the CSNCD Dataset and Its Applications

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The Comprehensive Dataset of the Chinese Seismic Network (CSNCD) is a high quality seismic dataset jointly developed by the China Earthquake Networks Center (CENC) and 31 provincial earthquake agencies. It encompasses over 1.3 million events and more than 45 million annotations labeled by catalogers. The dataset is characterized by a broad range of epicentral distances (0–180°), over 50 types of seismic phases, and a magnitude span from - 2.0 to 9.0, covering seven types of events. The CSNCD dataset is available for sharing through the China National Earthquake Data Center and has significant applications across various fields.

This dataset provides key information for booming data-driven geoscientific research, promoting new artificial intelligence algorithms in the era of big data and artificial intelligence. It provides an abundance of high quality samples for training deep learning models, such as the PRIME and PmP models, which demonstrate superior phase recall and event detection capabilities. These models possess the remarkable ability to classify event types and can achieve effective transfer learning with only a small number of samples. For earthquake monitoring and prevention, the CSNCD offers a solid foundation for application in diverse scenarios such as reservoirs, mines, oil and gas extraction, landslide monitoring and many other aspects. During the construction of the project of rapid intensity reports and earthquake early warning, CSN has been expanded several times. We'll release more observation products in quantity and variety through CSNCD, aiding seismology development.

## AS25-1380

# Rapid automatic assessment of felt likelihood of earthquakes: "Will they have felt it?"

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Natural Resources Canada (NRCan) is the authoritative source of information about earthquakes in Canada. A roster of on-call seismologists is on standby 24/7 to ensure that the information about significant earthquakes is rapidly available and accurate. The seismologist on call is automatically alerted for events over magnitude 4. However, earthquakes at lower magnitudes can be widely felt, particularly in eastern Canada where the regions with moderate intraplate seismicity roughly coincide with the highest population densities. When such events occur outside normal business hours the seismologist on call is sometimes not alerted until someone contacts our 24/7 message centre. Furthermore, earthquakes up to magnitude 5 offshore from Vancouver Island are relatively common but rarely felt, and therefore not as significant. Therefore, to minimize delayed and unnecessary callbacks, there is a need for rapid automatic assessment of the felt likelihood of earthquakes. I propose a method like PAGER (Jaiswal & Wald, 2011) that estimates the probability that a DYFI report will be filed rather than actual economic or human losses. A key "felt ratio" parameter is the proportion of the exposed population which responds by filing a felt report. It is calibrated using a database of "Did You Feel It?" (DYFI) reports filed with NRCan since 2010, ShakeMaps and census data. I look for diurnal, regional and historical trends in the felt ratio, and comment on uncertainties associated with a rapid notification that "this event is likely to be felt in these communities".

## AS25-1411

# A novel and modern Authentication method for FDSN web services

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The current specification of the authentication method for FDSN Web Services was adopted in 2013. The HTTP Basic Digest method proposed at that time was enough for the existing requirements.

Under this approach, authentication credentials are data center specific, which could be cumbersome if they operate as a federation, as users must register themselves at each data centre, and manage all usernames/passwords. To avoid this, data centres should synchronize their user databases, which would be a security risk.

Recently, new operational requirements emerged. For some funding agencies it is important to identify demographics of a facility's user base through identified access to measure the impact of their services and data. For data centres, insights about usage patterns are critical to improve services and resources allocation.

Nowadays, most identity providers (IdP) support modern authentication and authorization protocols (e.g. OAuth2, OpenID). They allow more interoperability and collaboration between services and clients. For instance, the possibility to decouple the IdP managing the authentication (e.g. eduGAIN, Google) from the Resource Provider (e.g. FDSN-WS). The connection between both entities is a token called JWT (JSON Web Token), that is issued by the former and consumed by the latter.

Here we present a flexible, modern standard of data access that carries with it the qualities of authentication and authorization. It has been submitted to FDSN for evaluation as a future standard for its web services. We expect that future versions of the software packages used in seismology will implement and adopt this standard to be authenticated (or optionally authorized).

## AS25-1434

# Analysis of the records from seismic station SRKO (Sofia University Seismic Network)

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Seismic station SRKO is the first broadband station from Sofia University Seismic Network (Bulgaria). It operates since August 2024, and seismic records have been used in various scientific investigations. The seismicity of Bulgaria is moderate concerning other neighboring countries, such as Greece and Turkey, but the weak seismicity is not well studied because not enough density distribution of seismic stations from the Bulgarian seismic network. The teleseismic events registered by Bulgarian stations are studied occasionally. We use the method of Golitzyn to localize small local events. We investigate the focal mechanisms of the moderate Bulgarian earthquakes (M<5) by collecting additional freely available seismic records and using INPAR method. The signals from several strong teleseismic events were analyzed to identify some core seismic phases. Surface-wave dispersion curve analysis is performed for several regional-to-teleseismic events to reveal structural characteristics between the source and SRKO station. A database with scientific results is created to be available for complex analysis.

## AS25-1435

# Long-Term Pressure Data from Offshore System of Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net)

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N-net is a newly developed observation network covering the previously unmonitored western region within the anticipated source area of the Nankai Trough earthquake. N-net consists of two subsystems: offshore system and inshore system. Offshore system was fully installed in January 2024 and has been undergoing trial operation since July of the same year, and transitioned to full operation in October. Each subsystem comprises 18 observatories connected in series via optical submarine cables, with each observatory equipped with seismometers and pressure gauges.

The pressure gauge installed in this system is a newly developed silicon resonant pressure sensor utilizing MEMS technology, designed simultaneously with the construction of N-net. This pressure gauge features a compact design, high sensitivity, and excellent stability, with minimal error caused by changes in its orientation. The pressure transmission system incorporating this pressure gauge is structured such that an elastomeric bellofram isolates the high-pressure electrical circuitry from seawater while transmitting external water pressure to the pressure gauge. As a result, the pressure gauge is not directly exposed to seawater.

Following the commencement of offshore system's trial operation, continuous data acquisition has been achieved, and daily tidal variations have also been recorded. Additionally, during the M7.1 earthquake that occurred in Hyuga-nada within the N-net observation area in August 2024, N-net successfully observed the tsunami generated by the earthquake. The maximum tsunami amplitude recorded was a few centimeters.

## AS25-1442

# Studying site effects through noise in Northern Greece

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Understanding station conditions is important for networks, and there are several ways of doing so. In a companion study, within EU project COREu that focuses on seismicity and hazard in the area of Kavala, we investigate stations in Macedonia and Thrace by compiling available metadata such as geology, topography, installation conditions, and meticulously analysing weak and strong-motion waveforms to estimate local site amplification using the horizontal-to-vertical spectral ratio (HVSR) technique. We also focus on its directional sensitivity. In this work, we turn our attention to noise recordings and assess site effects from continuous noise, along with assessing noise levels with respect to global models. This work intends to inform the study of background seismicity and seismic hazard within the COREU project in the Kavala area.

## AS25-1445

# The Seismological Network of Namibia

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Seismicity in Namibia is considered low to moderate, and it has been monitored since the 1900s mainly by International Seismological Centres. By 2010, Namibia had only six permanent stations with outdated seismic equipment that were continuously failing, making it difficult to monitor countrywide earthquake activities. With the advent use of social media, information on earthquakes felt by people spread much more rapidly and the Survey was unable to accurately confirm the event locations and magnitudes.

Currently, ten (10) seismological stations form the National Seismological Network (NSN)of Namibia. Namely (Windhoek, Rundu, Kamanjab, Aus, Ariamsvlei, Opuwo, Gobabis, Karibib, Katima and Tsumeb). The ten (10) permanent seismic stations are located approximately 500 km apart making it more challenging to detect micro seismicity. The recorded data is transmitted in real time via the GPRS mobile network to the main server located in Windhoek. The tenth station, which is the Tsumeb station, is part of the Global Seismological Network and Incorporated Research Institutions for Seismology (GSN/IRIS).

The highest event magnitude ever recorded in Namibia is a local magnitude 5.6 ***(ML)*** in 2009 and 2021 both in northwest Namibia. The national seismic data is used to provide monthly bulletins, monitors earthquakes countrywide and provides data for the Earthquake Hazard map of Namibia to be used for civil scientific applications land use planning and research. Additionally, the network provides data to the International Seismological Centre in the UK to contribute to the Global Seismic Hazard map.

Keywords: Seismological Network, Seismicity, Namibia.

## S03 Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

### AS25-0017

# Constraints on Shallow Earth Structure by the Compliance Method

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The compliance method is based on the analysis of co-located pressure and seismic data. It has been shown to provide constraints on shallow elastic structure, primarily the vertical shear modulus structure. The method was applied to observations on the ocean floor (e.g., Crawford et al., 1991) and on land (e.g., Tanimoto and Wang, 2019). These studies analyzed ambient seismic noise at low frequencies (< 0.1 Hz), where the coherence between surface pressure changes and ground motions can be high.

Most of these analyses relied on ambient seismic noise. In this paper, we demonstrate that a similar compliance approach can be used when large atmospheric pressure waves, excited by a volcanic eruption, propagate around the Earth. Specifically, we examine the eruption of Hunga Tonga-Hunga Ha'apai (hereafter referred to as Hunga-Tonga) on January 15, 2022. These pressure (Lamb) waves are accompanied by ground deformations in the solid Earth, which are an integral part of Lamb waves in the coupled Earth system. These pressure and vertical displacement are part of an eigenfunction of a Lamb wave mode, and we show how we can use these data to constrain the elasticity structures at shallow depths. Results on the analysis of data from Alaska and California will be presented.

## AS25-0045

# Seismic attenuation in the Middle Magdalena Valley, Colombia, and relation to fluid lubricated fault zones

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The Middle Magdalena Valley (MMV) is a region of intense deformation and high seismic activity at different depths, because of the convergence of the Caribbean, Nazca, and South American plates. Fault activity in the MMV could be influenced by fluid migration from natural or anthropogenic sources. Seismic attenuation is used to explore this link, as well as rock heterogeneity in the region. Intrinsic, scattering and total attenuation were calculated from 1635 earthquakes between 2016 and 2022. The results show adominance of intrinsic over scattering attenuation. Intrinsic attenuation was then related to structures on the Transandean seismic section. Additionally, a correlation was found between intrinsic attenuation and fluid sources, particularly precipitation, with a time lag of approximately one year. Water injection for enhanced oil recovery does not appear to have a notable effect on intrinsic attenuation based on our calculations. The Serranía de San Lucas west of MMV, is highlighted by intrinsic attenuation, suggesting fluid infiltration along strike-slip faults in this region, such as the Cimitarra fault. Less pronounced seismic attenuation is observed in the Bucaramanga and La Salina faults, east of the MMV. The results indicate a relationship between precipitation and active faulting through fluid lubrication, which could be relevant in the consideration of seismic hazard assessment in the region.

## AS25-0069

# Energy partitioning among strain components under equipartition in 3D homogeneous media

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The equipartition is an equilibrated state where energy is equally distributed in all modes. This state is expected for diffuse wave fields where multiple conversion scatterings occur. Under the equipartition, energy partitioning among different displacement components was calculated (e.g., Weaver, 1985; Sanchez-Sesma et al., 2008; Margerin, 2009). Recently, we can obtain strain seismograms with distributed acoustic sensing (DAS). However, only one component of strain tensors, axial strains along optical fibers, can be measured. Therefore, we need to know how seismic energy is partitioned into this single component. We are also curious about the late coda of DAS records. To address these questions, we have formulated energy partitioning among different strain components for 3D homogeneous full-space and half-space. According to the formulation, we can know how P, SV, SH, and Rayleigh waves contribute to each strain component and how these partitioning changes with depth. The effect of the free surface becomes smaller with depth. Then, results at deeper depths in half-space are found to approach the results for 3D full-space. This agreement corroborates our present calculations. This study leads to a better understanding of the coda of DAS records, which will help us interpret both of borehole and surface DAS data.

## AS25-0103

# High-resolution 3D crustal structure of Kumaun-Garhwal (Central) Himalaya: insights from joint inversion of surface wave and body wave datasets

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Gaining insight into the crustal structure of the Himalayas and the geometry of the Indian plate underthrusting beneath the Himalayan arc is critical for understanding regional tectonics and assessing earthquake potential. In this study, we present a high-resolution 3D model of compressional wave (Vp), shear wave (Vs), and P-to-S wave velocity ratio (Vp/Vs) for the Kumaun-Garhwal Himalaya, a seismically active region proposed as a potential site for a future great earthquake. To construct this model, we performed a joint inversion of surface wave and body wave datasets. This approach addresses the limitations of the individual methods, leveraging the complementary strengths to produce more realistic crustal structures. We integrated data from both body and surface waveforms recorded by the 51 broadband seismic stations that were operational from November 2006 to June 2008. Our findings offer a comprehensive model of the crust in the study area. The Main Himalayan Thrust (MHT) in the region is found to be characterized by a flat-ramp-flat geometry, which has significant implications for seismic hazard analysis. Additionally, relocated seismicity and velocity anomalies shed light on the crustal composition and its influence on earthquake nucleation processes in this seismically critical region. These findings enhance our understanding of the geodynamic processes shaping the Himalayan arc and contribute to more accurate earthquake risk assessments.

**Keywords**

Seismic tomography; Continental tectonics; Main Himalayan Thrust; Crustal imaging

## AS25-0198

# Estimation of seismic attenuation and scattering structures from the shape of seismogram envelopes: method and application in southwestern Japan

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Recent developments in modeling seismogram envelopes and dense seismic networks enable us to estimate the heterogeneous distribution of seismic attenuation and scattering parameters. Here we propose a method to estimate the 3-D distribution of seismic attenuation and scattering parameters from the shape of seismogram envelopes. In the method, we first estimate attenuation and scattering parameters for each seismogram envelope via the envelope fitting, then we map the parameters into 3-D space using sensitivity kernels of both parameters. For simplicity, we adopt the acoustic radiative transfer theory with non-isotropic scattering coefficients based on the Born approximation in the envelope fitting and the calculation of sensitivity kernels. We apply the proposed method to estimate the 3-D seismic attenuation and scattering structure of southwestern Japan. We selected 418 earthquakes whose focal depths were less than 100 km and magnitudes were between 3.0 and 4.5. We successfully measured the attenuation and scattering parameters for 4,233 and 4,090 envelopes in the frequency range of 1–2 and 2–4 Hz, respectively. We then mapped the attenuation and scattering parameters in southwestern Japan. We confirmed that the proposed method could retrieve a heterogeneous distribution of attenuation and scattering parameters although the amplitudes of anomalies were biased. The estimated distribution of attenuation and scattering parameters corresponds to the tectonics of the target area: strong attenuation and scattering were observed near active volcanoes.

**Acknowledgment**

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## AS25-0201

# Seafloor seismograms reveal crustal S-wave velocity contrasts in the Guerrero seismic gap, Mexico

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The Guerrero seismic gap (G-GAP) in the Mexican subduction zone has not experienced a megathrust earthquake since 1911. Thanks to seismic observation campaigns done with ocean bottom seismometers (OBSs) since 2017, Plata-Martínez et al. (2021) first detected shallow tectonic tremors in the G-GAP and identified a "silent zone" characterized with low seismic activity of both slow and fast earthquakes. To uncover the structural heterogeneity within the G-GAP and understand the seismological conditions of slow and fast earthquakes, we examined S-wave velocity contrasts using receiver-side Green's functions (GFs; Akuhara et al., 2019) derived from OBS data collected between 2017–2023.

Before computing GFs, we corrected horizontal sensor orientations based on Rayleigh-wave particle motion (e.g., Stachnik et al., 2012; Sawaki et al., 2023). The orientation uncertainties were mostly less than 12, making them suitable for receiver function analysis. We computed GFs using Gaussian lowpass filters of 0.6, 1.0, and 2.0 Hz. The resulting GF traces at the western edge of the silent zone showed several strong phases around 2–4 s, which we attributed to the plate interface or some structural boundaries within the accretionary wedge. Notably, these phases exhibited clear back-azimuthal variation. Other GF traces near the silent zone also showed similar variations. These results suggest the presence of strongly dipping or anisotropic structures around the silent zone.

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## AS25-0380

# Crustal structure of Mutnovsky volcano (Kamchatka) and its surroundings from ambient noise tomography

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Mutnovsky volcano, located in Kamchatka, Russia, is a highly active volcano characterized by frequent ash and gas explosions. Its explosive eruptions, the most recent of which occurred in 2013, pose a threat to the nearby city of Petropavlovsk-Kamchatsky (70 km away) and the Mutnovsky Geothermal Plant (MGP), located near the volcano within a fumarole field. While the mantle wedge structure beneath Mutnovsky has been studied, the upper crust structure remains poorly understood.

The research utilized continuous seismic data collected from a temporary seismic network surrounding Mutnovsky during 2023–2024 consisting of 65 temporary stations and 4 permanent stations of the Kamchatka Branch of the Geophysical Survey RAS. Vertical components of the records were processed to construct cross-correlation functions, from which Rayleigh surface wave group velocity dispersion curves were extracted. To enhance the signal-to-noise ratio, the SVD-based Wiener filter was applied, and the covariance matrix spectral width was analyzed. The resulting dispersion curves were then used in a seismic tomography algorithm to compute a three-dimensional shear-wave velocity model. Several "Checkerboard" tests were performed to evaluate the model's robustness.

The model reveals a low-velocity anomaly at a depth of 2–5 km below sea level beneath Mutnovsky, likely corresponding to the magma chamber. Another low-velocity anomaly is observed beneath the MGP at a depth of 2–5 km below the surface, linked to the surface by a narrow vertical anomaly. It may represent an intrusion acting as a geothermal energy source. The study provides new insights into the Mutnovsky hydrothermal-magmatic system.

## AS25-0449

# Imaging shallow velocity structure of Lijiang-Xiaojinhe Fault based on dense array

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The southeastern margin of the Tibetan Plateau is one of the most seismically active regions in the world. Among them, the Chuan-Dian Rhombic Block has a complex tectonic activity, with intense and frequent seismic activity. The Lijiang-Xiaojinhe Fault is an important secondary boundary fault within the Chuan-Dian Rhombic Block, located in the upper crust (≤ 30 km). It marks the edge of the high-velocity anomalies for both P-waves and S-waves. The crustal deformation difference between the blocks on either side of the fault zone is significant, and a large amount of evidence indicates that the Lijiang-Xiaojinhe Fault has been highly active since the Holocene.

Based on the dense array observation data, studying the fine structure of fault zones is one of the effective methods. This study uses the short-period dense array observation network established in the Lijiang-Xiaojinhe Fault and Ninglang Fault regions, and employs background noise imaging techniques to obtain high-resolution shallow velocity structures. It aims to finely characterize the geometric morphology of the fault zones, describe the topographic undulations of the sedimentary layer basement, identify the sedimentary layer structures in the study area, and construct a detailed velocity structure model for the shallow layers of the fault zones in the research region.

## AS25-0472

# Ambient Noise Tomography beneath the Banda Basin reveals new insights into the Arc-Continent Collision Zone

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The Banda region is a natural laboratory for continent-arc collision studies. However, much of the seismic structure beneath this region is poorly understood. Here, we present a new 3D shear velocity model and Moho topography map for the Banda region. Rayleigh waves group and phase velocities are extracted from dispersion analysis obtained from ambient noise cross-correlations. We apply a nonlinear joint inversion of the group and phase local dispersion derived from tomography maps to obtain 1D velocity-depth profile at each node of a regular grid. Our velocity model of the shallow lithosphere below the Banda Basin highlights different velocity features relating to the tectonics of the Banda region. At shallow depths, high velocities below the North Banda and South Banda Basin points to an oceanic crust. The Banda ridges show up in our model as a low velocity feature separating the high velocities below the north and south Banda basins. We image the inner and outer Banda Arc as two different velocity structures, with high velocities observed below the inner arc islands and low velocities mapped below the outer arc islands, in agreement with previous studies. Our Moho topography map shows complex lateral variations in crustal thickness but very consistent result within the tectonic context of the Banda region and correlate with estimates from receiver function and P-coda auto-correlation studies where available.

## AS25-0476

# Estimating Subsurface Velocity Structure Based on Microtremor and Earthquake Horizontal-to-Vertical Spectral Ratios and Phase Velocity Inversions in Southeastern Taiwan

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In 2022, a local magnitude 6.4 foreshock and a local magnitude 6.8 mainshock occurred in southeastern Taiwan (2022 Guanshan-Chihshang earthquakes). This earthquake sequence caused severe damage to buildings including even collapse, infrastructure, and bridges. Although it is still under debate which fault caused the earthquakes, the area in southeastern Taiwan still has a high likelihood for disastrous earthquake occurrence based on probabilistic seismic hazard analysis. In order to reduce the potential seismic risk, understanding the cause of high seismic hazard is necessary. The information about the detailed subsurface velocity structure and the depth of seismic bedrock (Vs=3 km/s) around the source area would be helpful for seismological and earthquake engineering research such as waveform inversion and ground motion simulation. In this study, we conducted three microtremor arrays near the strong motion stations (G020, F042, and EYUL) which recorded the strong ground motion during the earthquakes. We performed the frequency-wavenumber method to estimate Rayleigh wave phase velocity and we estimated the averaged microtremor horizontal-to-vertical spectral ratio (MHVR) of each array. Also, we estimated the earthquake horizontal-to-vertical spectral ratios (EHVRs) of the strong motion stations. Finally, we obtained a detailed velocity model from surface down to seismic bedrock for each strong motion station based on phase velocity, MHVR, and EHVR inversions. As a result, the depths of the seismic bedrock for G020, F042, and EYUL are estimated to be 2402 m, 2140 m, and 2305 m, respectively, which are shallower than those in the previous study (Huang et al., 2014).

## AS25-0514

# Near-Surface Structure Imaging across the Xichang Segment of the Anninghe Fault with a linear dense seismic array

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The Xichang segment of the Anninghe Fault, with a history of strong earthquakes, is currently in a high stress lockup state, indicating a significant risk for future seismic activity. To address this, the China Seismic Experimental Site project plans to deploy a series of observational systems, including fiber-optic sensing, for continuous monitoring in the region. As a preliminary survey, we deployed a 45-km linear dense seismic array using 152 short-period nodal sensors for one month. Data analysis using the Horizontal-to-Vertical Spectral Ratio (HVSR) method identified three site effect patterns in the frequency domain: no peak, single peak (10–20 Hz), and double peak (0.3–0.5 Hz and 10–20 Hz). These patterns indicate impedance interfaces at depths ranging from several meters to hundreds of meters. P-wave first arrivals showed delays of approximately 20 milliseconds in the Anninghe valley, correlating well with deeper interfaces identified by HVSR. We also applied the High-Resolution Linear Radon Transform technique to suppress zero-time-lag noise in Cross-Correlation Functions, thereby improving dispersion quality. Rayleigh wave group velocities (0.2–7 s) were extracted and used for one-step inversion to obtain the shear-wave velocity structure. The results from these methods are consistent, confirming the shallow subsurface structure and amplification effects. This provides a robust foundation for future observational engineering efforts.

## AS25-0555

# Geothermal reservoir characterization and monitoring from Three-Component beamforming of ambient seismic noise

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Geothermal energy is an essential low-carbon energy resource for the energy transition. The subsurface characterization of geothermal fields is essential for expanding this resource. Often, faults and fractures provide the secondary permeability required for hydrothermal circulation. Anisotropy in the ambient seismic noise wavefield is a novel method for constraining these faults and fractures within geothermal settings at an inexpensive cost.

We use the code package B3AM to perform three-component (3C) beamforming of ambient noise. It is an array-based method that extracts the wave types, directions, and phase velocities of coherent waves as a function of frequency from ambient seismic noise, providing a comprehensive understanding of the seismic wavefield. Rayleigh wave propagation velocities are observed to differ according to the strike directions of faults.

Numerical modelling of Rayleigh waves and analysis of Rayleigh waves from two geothermal case studies (Los Humeros Geothermal field, Mexico and Eden Geothermal, UK) were assessed to ascertain Rayleigh wave anisotropy for fracture characterization within geothermal settings. Array effects, instrument type, and varying geological complexity all impact the quality, reliability and detail of anisotropic results in the subsurface, all of which will be discussed. Fast and slow directions of Rayleigh wave propagation with our detailed analysis of Rayleigh wave behaviour can indicate fault strikes within the subsurface; furthermore, varying Rayleigh wave frequency can convey the maximum depth of penetration of these faults.

## AS25-0557

# Comprehensive seismic site response evaluation in Oltenia region utilizing combined ambient and earthquake HVSRs

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The Oltenia region, situated in the SW part of Romania, is known for its crustal seismic activity, attributed to its complex tectonic and geological characteristics. These features can amplify seismic waves, giving a high variability of the ground motion in the area. Recent seismic activity, particularly the February 2023 earthquakes, emphasize the area's susceptibility to such occurrences. The sequence included two significant shocks measuring 4.8 Mw on February 13 and 5.4 Mw on February 14, followed by over 4000 aftershocks within a year. The same region experienced notable earthquakes in the past, like the ones produced on July 9, 1912, June 20, 1943, and May 4, 1963, with different impacts on local communities.

This study focuses on characterizing the seismic response of the Oltenia zone by calculating the Horizontal-to-Vertical Spectral Ratio (HVSR) using ambient vibration and earthquake data from seismic stations in the region. The dataset consists in continuous recordings of ambient vibrations and significant earthquakes (Mw>3.5) from both permanent and temporary monitoring stations established during recent seismic activities, managed by NIEP.

The HVSR method is a recognized approach for assessing site effects and identifying a site's fundamental frequency of resonance. Analyzing both ambient vibrations and earthquake data will provide insights into local soil conditions and their potential to amplify seismic waves. This study aims to enhance understanding of local structure and its seismic response, offering valuable information for earthquake engineering and risk mitigation strategies in the Oltenia region.

## AS25-0609

# Scattering and absorption imaging of the Hengill high-temperature geothermal area (SW Iceland)

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Seismic scattering and absorption are highly sensitive to crustal rheology, fracturing, and fluid/melt content, making them beneficial for geothermal exploration. We present the first 3D scattering and absorption imaging of the Hengill region (SW Iceland) using peak delay and Q-coda methods. The results reveal crustal structures beneath the Hengill central volcano, the Nesjavellir geothermal field, and two non-harnessed areas: Mosfellsheiði and Ölkelduháls.

A high-scattering shallow anomaly marks the Hengill fissure swarm, while deep low-scattering zones suggest sub-horizontal intrusions reducing seismic scattering. At Nesjavellir, high-scattering and high-absorption volumes align with a high-Vp/Vs anomaly, indicating fluid- or melt-filled fractures. Similar anomalies in Mosfellsheiði and Ölkelduháls suggest possible geothermal reservoirs.

Our study highlights scattering and absorption imaging as powerful tools for geothermal exploration. We recommend Mosfellsheiði for potential development, emphasizing that despite the absence of surface manifestations, the resource should be harnessed, as it exhibits similarities (e.g. seismicity bordering the anomaly) to the successfully exploited Nesjavellir geothermal field.

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## AS25-0675

# Estimation of the subsurface structure and its seismic amplification characteristics of the Shonai Plain, Japan derived from microtremor observation records

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The 1894 Shonai earthquake caused seismic damage in the Shonai Plain in the western Tohoku region, nothern Japan. Based on damage survey reports and historical materials, damage to buildings was spread throughout the Shonai Plain, and areas with heavy damage and/or damage concentrated area were observed. The heterogenous damage distribution is caused not only by the seismic source but also influenced by the site characteristics. To understand the correspondence between the damage distribution and the site characteristics, array and single-station microtremor measurements were performed in the Shonai Plain. The subsurface structure and its seismic amplification characteristics are derived from the observation records. Records from nine large arrays (maximum length of side of triangle L=135 m) and ten small arrays (L=30 m) were used to estimate the Rayleigh wave phase velocity (RWPV) at each array and 132 single-stations were used to derive the Horizontal-to-Vertical Spectral Ratios (MHVR) at each station. RWPVs and MHVRs were inverted to estimate the velocity structure from the surface to the seismic bedrock. From the estimated velocity structure, the transfer function for S-wave was calculated to derive the amplification factor at several frequency ranges. As a result, the distribution of the high amplification factor around 1 Hz showed a good match to the heavily damaged area during the 1894 Shonai earthquake.

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## AS25-0735

# Study of crustal and upper mantle structure beneath the Kenyan Rift using Receiver Function Analyses

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The East African Rift System (EARS) is a prominent continental rift zone, extending over 3,000 km from the Afar Triple Junction to Mozambique. Its Kenyan segment features fault-bounded basins, volcanic activity, and seismicity, making it an ideal site for investigating crustal structure and rifting mechanisms. Previous geophysical studies revealed significant variations in crustal thickness along the rift axis, with thinning toward the north and thicker crust beneath the Tanzanian Craton and Mozambique Belt. However, detailed investigations with broader spatial coverage remain limited. This study utilizes data from 20 broadband seismic stations, including temporary deployments like GRAILS and permanent stations such as KMBO. Receiver function (RF) inversions and apparent S-wave velocity analyses reveal localized crustal thinning within the rift zone. A high-velocity lower crust (HVLC) beneath the rift is interpreted as modified mantle lithology, suggesting crustal thinning accompanied by anomalous upper mantle material. A regional Moho depth model integrating these findings with prior studies confirms localized thinning along the rift. These results enhance understanding of crustal dynamics in the Kenyan Rift and provide insights into mechanisms driving continental rifting processes.

## AS25-0886

# Estimation of frequency and depth dependent intrinsic and scattering attenuation of seismic shear waves

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The estimation of seismic attenuation parameters of the Earth is more difficult than the estimation of seismic velocities for two reasons: (1) Scattering attenuation as well as intrinsic absorption contribute to the attenuation of seismic waves and it is essential to separate these two effects. (2) Seismic attenuation parameters are inherently frequency dependent, whereas frequency dependence of seismic P- and S-wave velocities can be neglected in almost all cases. We develop a computer code, 'QEST - Q estimation' based on a forward modelling using radiative transfer theory in depth-dependent velocity and attenuation models and a global inversion scheme based on a genetic algorithm. Besides frequency- and depth-dependent intrinsic as well as scattering attenuation parameters, earthquake source spectra and frequency dependent receiver site amplifications are a result of the inversion with QEST. We applied the technique to seismograms of earthquakes in the Upper Rhine Graben, Germany, and in the Leipzig-Regensburg fault zone, Czech German border region, as examples of regions with thick sedimentary layers and without thick sedimentary layers, respectively. Results show a clear depth and frequency dependence of both, scattering attenuation as well as intrinsic absorption, within the thick sediments of the graben. The region without thick sediments, on the contrary, shows clear frequency dependence of attenuation parameters but less depth dependence.

## AS25-0935

# Site effects evaluation using natural noise at the national seismic stations network of Morocco

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Morocco, being a country with diverse soil cover, experiences variations in earthquake ground motion due to the presence of thick sediments in some areas. This was evident during the large earthquake on September 8, 2023, in Al Haouz, Morocco, which resulted in at least 2960 deaths. Unfortunately, there is currently a lack of available estimates regarding site effects in Morocco based on noise recordings. For this purpose, 16 stations from the CNRST network, distributed across different geological domains, are used. The objective of this study is to estimate the site effect in Morocco using a local seismic noise network. Different parameters are extracted, such as fundamental frequency, fundamental amplitude, and vulnerability index (Kg) value. In addition to, ground shear strain (GSS) analysis could be employed to assess the risk of landslides. The thickness of sediments of each seismic station using seismic noise data have been calculated. High frequencies between 3–4 Hz are found in three seismic stations (RTC, AKL, and OUK), suggesting thinner soil layers, which indicate a high cohesion of the sediment. Lower frequencies (1–2 Hz) found at other stations, which indicate thick soil sediments. The vulnerability index (Kg) for all seismic stations is less than 20, which means no dangerous situation is detected. Most of the ground shear strain values are between $10^{-6}$ and $10^{-7}$, which means that we are in the elastic domain. The results of this study provide us with a general view about the variations in the subsurface rocks in their content and compaction.

## AS25-0997

# Automated and Efficient Surface-wave Phase Velocity Estimation and Quality Control: Ambient Noise Tomography in The Big Data Era

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Ambient noise tomography (ANT) has evolved from pioneering laboratory experiments into a widely used method for imaging Earth's subsurface at various scales. A standard framework involves selecting concurrent data windows from two stations, removing trends, normalising in time and frequency domains, cross-correlating (CC) the normalised data, and stacking CCs to obtain the noise correlation function (NCF). Surface wave dispersion properties between station pairs are then extracted from the NCF. A common approach of extracting dispersion curves matches the zeros of the NCF spectrum with those of the first-kind Bessel function. However, this method does not account for missing or extra zeros in the spectrum, leading to discontinuities in dispersion data. Researchers have employed various ways to limit such encounters, via employing various smoothing operators or by manually checking the data.

In this study, we introduce an empirical relationship between zero spacing in the spectrum and inter-station distance, termed the empirical zero-distance law (EZDL). We use EZDL to develop a fully automated workflow that can navigate through missing or extra zeros in the spectrum. Additionally, we propose a new quality control metric, the well-placed zero ratio (WZR), which outperforms traditional metrics such as signal-to-noise ratio (SNR) in tracking surface wave arrivals. We demonstrate how applying EZDL for dispersion curve tracking and WZR for quality control significantly enhances ANT imaging results for the AusArray deployment in Northern Territory, Australia. AusArray, initially funded through the Exploring for the Future program continues with an expanded deployment as part of the Resourcing Australia's Prosperity initiative.

## AS25-0999

# Ambient Noise Tomography of The Australian Continent Using 40 Years of Passive Seismic Records in Australia

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The Australian continental crust has a rich and complex tectonic history, reflected in seismic tomography by sharp velocity contrasts. In this study, we utilise data from all available temporary seismic deployments in Australia through AusPass (https://auspass.edu.au/), the Australian Permanent Seismic Network (ANSN), and the AusArray network (https://www.eftf.ga.gov.au/ausarray), which covers the continent in a 2° × 2° array. AusArray, initially funded through the Exploring for the Future program continues with an expanded deployment as part of the Resourcing Australia's Prosperity initiative. We compute hourly cross-correlations and stack them to generate noise correlation functions (NCFs) for each station pair. Dispersion curves are extracted from NCF spectra using an automated workflow, enabling us to perform ambient noise tomography (ANT) across the Australian continent.

Our ANT model, constructed from surface wave velocity maps from 60s to 2s periods, resolves well-known major sedimentary basins as well as several recently discovered smaller basins. We validate our model against deep-crustal active seismic profiles in Australia and observe remarkable agreement between the two datasets. Additionally, we compare our results with borehole data, interpreted basin analysis from gravity, magnetic, and active seismic surveys, revealing the lateral extent and depth of major basins such as the Canning, Officer, and Great Artesian basins. In the Great Artesian Basin, we detect extremely low velocities in regions with significant water saturation. These findings highlight ANT as a robust tool for imaging first-order, large-scale crustal structures, offering valuable insights into Australia's geological framework.

## AS25-1005

# Exploring The Subsurface Structure: Seismic Refraction Tomography at Lousal Mine—Portugal

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Muography was first applied in Portugal through the LouMu project, a collaboration among various institutions. A previous study used this method to detect the Late Variscan NNE-directed Corona fault at Lousal Mine (Iberian Pyrite Belt, SW Portugal), revealing its location and brittle deformation, later confirmed by the velocity model. The project integrated seismic refraction to image the subsurface and validate the muography-derived density model.

Seismic imaging used an unconventional 3D setup with 256 surface shot points in a 45 m × 45 m grid and 48 geophones arranged in an H-shape inside the Waldemar mine gallery. This innovative arrangement ensured comprehensive ray coverage, overcoming limitations of previous 2D surveys that were unable to fully reveal the targeted structure. The generated model accurately constrained the main fault extension, showing strong correlation with geological structures and enabling the identification of secondary faults.

The innovative acquisition geometry required ATOM3D software to account for the unique geophone-source arrangement, highlighting the novelty of our approach and its impact on future geophysical investigations.

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## AS25-1036

# Temporal seismic velocity monitoring in the western Bohemian Massif area with the help of ambient noise cross-correlation

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Changes in temperature and precipitation loads on crustal rocks can evoke responses that trigger seismic activity, alter seismic velocities, and affect crustal strain. Keeping track of these responses is beneficial for monitoring the changing stress levels, which frequently result in seismic events, faulting, and the behaviour of subsurface fluids. Traditionally, this monitoring has relied on earthquakes or human-made explosions. However, a significant challenge is that it is uncommon to see repeated earthquakes with the same source locations and mechanisms, making their occurrence unpredictable. Additionally, conducting human-made explosions regularly can be quite costly. In the past decade, the passive imaging method has gained popularity among researchers because it allows for consistent source positioning for each receiver over time, along with the continuous collection of data.

In this study, we present our findings on the relative changes in seismic wave speeds (dv/v) within the Western Bohemian Massif region, specifically the Saxothuringian unit, derived from an analysis of four years of seismic noise recorded at 20 stations within the regional seismic network. We evaluate the efficacy of the 'stretching' and 'doublet' techniques in this context, with the aim of assessing their potential for estimating variations in seismic velocity. Our results from both methodologies reveal notable peak-to-peak seasonal fluctuations of approximately 0.75 per cent in dv/v, exhibiting periodicity ranging from annual to sub-annual within the 0.1–0.5 Hz frequency spectrum. Initial phase measurements suggest that the predominant influence on these variations is atmospheric temperature changes, in short-duration rainfall also significantly impacts dv/v alterations.

## AS25-1051

# Mantle flow directions reveal a vertical slab window beneath the Bransfield strait region, Antarctica

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Seismic anisotropy measurements provide key insights into asthenospheric flow patterns influenced by sublithospheric structures, such as subduction zones and slab windows. The temporary deployment of the BRAVOSEIS seismic network in the Bransfield Strait, Antarctica, has significantly enhanced station coverage, enabling a more detailed investigation of mantle dynamics. To characterize mantle anisotropy, we analyze shear wave splitting of core phases, extracting fast polarization directions and delay times.

Our results indicate that upper mantle anisotropy generally aligns with expected subduction-driven flow patterns. However, significant deviations suggest the presence of a vertical slab window in the Phoenix slab. These anomalies are consistent with numerical models predicting asthenospheric flow. Additionally, P-wave receiver function analysis further supports this interpretation, providing independent evidence of slab tearing. These findings enhance our understanding of subduction processes in the Bransfield Strait.

## AS25-1075

# Dense array deployment in the Alto Tiberina Fault zone: Insights into Seismicity and Fault Dynamic

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We present the preliminary results of a seismic acquisition experiment carried out within the MUSE (Multiparametric and Multiscale Study of Earthquake Preparatory Phases in the Central and Northern Apennines) project in the area comprising the Alto Tiberina fault system in the Northern Apennines of Italy. This area is characterized by high geodetic strain-rates, with ~3 mm/yr of SW-NE extension partially accommodated by aseismic creep on the low angle Alto Tiberina normal fault. High angle hanging wall faults play a role in seismogenic ruptures and during the occurrence of seismic swarms.

We have installed a dense array of 186 nodes (GSB-3 recorder and GS-One LF triaxial sensor by Geospace Technologies®) along two approximately linear stretches converging on a cluster of three stations located near an industry (cement factory) previously identified as a source of seismic noise.

The primary objective was the reconstruction of seismic body waves through the cross-correlation of continuous recordings at different pairs of stations. Once identified, the application of interferometric techniques on cross-correlations between stations should allow us to gain new insights into the evolution of faults at seismogenic depths and improve our understanding of the earthquakes preparatory phase, possibly highlighting seismic velocity variations with time.

Here we provide an overview of the experimental phase, together with initial data analysis and quality control. A review of seismic events recorded during the recording period and a first attempt at body-wave reconstruction are also presented.

## AS25-1103

# Data-driven characterization of full seismograms in heterogeneous media

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Seismic wave propagation through the Earth's crust is influenced by interactions with subsurface heterogeneities, giving rise to the coda of the seismograms. While scattering phenomena are frequently analyzed using probabilistic frameworks such as Radiative Transfer Theory, the underlying process is inherently deterministic. It encodes information about all wave interactions along the path from the source to the receiver. Despite the apparent complexity of the signal, this complexity can, in principle, be unfolded to reveal the properties of the medium and its heterogeneities. In this study, we employ unsupervised machine learning techniques to directly characterize the scattering properties of a highly heterogeneous medium by analyzing full synthetic seismograms. We employ a two-layer deep wavelet scattering network to extract robust representation from the seismograms. Principal Component Analysis is then applied to identify the number of principal components of the scattering coefficients that reach a predefined variance threshold. In this study, we use synthetic data which are generated for 7800 sources distributed within a deep structure of a magmatic plumbing system, recorded at five surface stations using a 2D spectral-element method. The model for this environment is based on the thermo-elastic simulations of dyke and sill intrusions. Our results demonstrate that the statistical properties of the medium correlate well with the estimated local complexities derived from seismic signals. This approach offers a novel and data-driven means of characterizing subsurface heterogeneities through the analysis of complete seismograms and holds promise for enhancing space-time monitoring of subsurface conditions in highly heterogeneous regions.

## AS25-1151

# S-wave velocity uppermost mantle structure beneath the Central Mariana subduction zone inferred from ambient noise tomography

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Understanding the structure of subduction zones is essential for elucidating water transport mechanisms into the mantle, as the subducting slab serves as the primary conduit for water entering the deep Earth. The Central Mariana subduction zone exhibits key geophysical processes, including forearc serpentinization evidenced by serpentinite mud volcanoes, arc volcanism driven by slab-derived volatiles, and the formation of new oceanic lithosphere at back-arc spreading centers. In this study, we estimated fundamental-mode Rayleigh-wave group- and phase-velocity dispersion curves for periods ranging from 3 to 35 s, first-overtone Rayleigh-wave phase-velocity dispersion curves for periods of 5–13 s, and fundamental-mode Love-wave group- and phase-velocity dispersion curves for periods of 7–18 s. These estimates were derived using continuous seismic data from 32 ocean-bottom seismometers and 19 island stations. Additionally, we applied the C3 method to determine group and phase velocities between asynchronous station pairs. By jointly inverting the multimode Rayleigh-wave dispersion curves, we constructed an S-wave velocity model with resolutions down to 100 km depth. Furthermore, by jointly inverting Rayleigh- and Love-wave dispersion data, we computed a radial anisotropy model down to crustal depths. The resulting velocity model reveals prominent low-velocity anomalies along the subducting slab down to ~40 km depth, indicative of serpentinization, as well as beneath the volcanic arc (60–90 km depth) and the back-arc spreading center (10–30 km depth). Notably, we observe a structural connection between the low-velocity anomalies beneath the volcanic arc and the back-arc spreading center, suggesting a pathway for material and fluid transport.

## AS25-1233

# Medium velocity variations at Campi Flegrei caldera (Southern Italy) imaged by coda wave interferometry: Application to repeating earthquakes

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The Campi Flegrei Caldera (Italy) is an active volcanic system that has experienced significant seismic activity in recent years. In this study, we analyzed a catalog of approximately 12,000 earthquakes that occurred between 2014 and 2024 to estimate medium velocity variations by coda wave interferometry (CWI) of repeating earthquakes. We first grouped the events via a hierarchical agglomerative clustering technique and identified repeaters as intra-cluster events with high waveform similarity. Then, we applied CWI to pairs of repeating earthquakes to estimate medium velocity variations over time and space. We investigated temporal pattern and correlation between medium velocity variations, repeater density and spatio-temporal distribution, deformation rate. Our preliminary results indicate that most repeating earthquakes occurred between January 2022 and November 2024. We found moreover a broad correlation between relative medium velocity variations and earthquake density in this time interval, with positive velocity changes detected at multiple sensors and mostly occurring during earthquake swarm activity.

## AS25-1260

# Insight on the 3D subsurface structure of the Paliki Peninsula (Kefalonia, Greece) from a large scale geophysical field campaign

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The Paliki Peninsula of the Ionian Kefalonia Island (Greece) is located in one of the most active seismotectonic regions of the Mediterranean Sea, east of the major Kefalonia-Lefkada transform fault. Paliki has been repeatedly hit by moderate to large earthquakes up to Mw 7.0. A joint geophysical field campaign was organized in 2024 to develop a new 3D subsurface model for understanding site effects and to compute a more detailed velocity model for accurately locating earthquakes. Eight cross-profiles and one array were installed on Paliki, using 27 SmartSolo 3C nodes and two Tromino instruments. Ambient noise measurements were carried out at 220 locations, resulting in a total of 3225 hours of continuous data. Several small earthquakes were recorded that could not be located with the permanent seismic network alone.

Array- , cross-correlation and Horizontal to Vertical Spectral Ratio (HVSR) techniques were applied to model the sedimentary cover and the variation in bedrock depth. Array data were processed with fk and inverted using dinver. Preliminary results show increasing thickness of Miocene marls deposits from west to east, overlaying a bedrock of Eocene limestones deeping to several hundreds of meters deep towards the eastern shoreline of the peninsula. To our knowledge, this is the first time that such large-scale fieldwork has been performed on an Ionian Island and the recorded data will stimulate new research studies, contributing significantly to more precise earthquake locations, and more accurate future local hazard assessments and risks evaluations.

## AS25-1300

# Spatial and Temporal Variations in Attenuation Before and During the February 6, 2023, Earthquake Sequence in Türkiye

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On February 6, 2023, a powerful Mw 7.8 earthquake, referred to as the Kahramanmaraş earthquake, struck the region between southern Turkey and northern Syria, causing ruptures along several southwestern segments of the East Anatolian Fault System (EAFS). Nine hours later, the Mw 7.6 Elbistan earthquake occurred, impacting an east-west oriented fault near the main branch of the EAFS. Furthermore, the Mw 6.4 Antakya aftershock followed, originating from a bifurcation of the EAFS.

The study of seismic attenuation provides information about variations in the crustal properties and heterogeneities (e.g., fractures, temperature, and pressure variations), and its imaging can reveal the spatial variations of these properties.

This work aims to present a 2D imaging of seismic wave scattering and absorption variations before and during the February 6 earthquake sequence, examining their spatial and temporal changes across different frequency bands. We utilized two datasets: the first, covering the pre-sequence phase, from January 2020 to February 5, 2023 (~48000 waveforms); and the second, which begins with the February 6 event till the end of May 2023 (sequence phase, ~238000).

We calculated the peak-delay parameter and the $Qc^{-1}$, which serve as proxies of seismic scattering and seismic absorption, respectively. Additionally, we applied the coda normalization method to obtain the total attenuation of the area. The preliminary results indicate a difference between the pre-sequence and the sequence phase, with increased scattering and absorption along the main branch of the EAF. Between the EAF and the North Anatolian Fault/Bingol area, we observe consistently high scattering and absorption.

## AS25-1332

# Crustal Heterogeneity and Fluid Signatures from 3D Seismic Attenuation Imaging in the South Carpathian Bend Region

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In February 2023, a significant earthquake sequence struck the boundary between the Southern Carpathians and the Moesian Platform, raising questions about the underlying mechanisms driving seismicity in this region. This area, shaped by complex interactions between an obliquely thrusted microplate and the Moesian Platform, has long been a zone of deformation. However, the role of fluids, stress redistribution, and lithospheric properties in triggering such clusters of earthquakes remains poorly understood.

To better understand the processes controlling earthquake generation at the contact between the Southern Carpathians and the Moesian Platform, we built the highest-resolution 3D seismic attenuation model by applying the Multi-Resolution seismic Attenuation Tomography algorithm (MuRAT). To highlight the attenuation patterns, we measured S-wave peak delay times (Tpd) and late-time coda quality factors (Qc) across multiple frequency bands (3, 6, 9, and 12 Hz) for weak to moderate crustal earthquakes ($2.5 \leq ML \leq 5.7$) recorded between 2014 and 2024 by the permanent and mobile stations of the Romanian Seismic Network.

Tpd measurements reveal pronounced structural heterogeneity across all frequency ranges. High-absorption regions are observed consistently across the entire depth range analysed. These features likely reflect the existence of fluid pathways that, depending on frequency, migrate across different scales through the crust.

## AS25-1388

# Potential and limitations of body-wave seismic noise tomography and P-to-S velocity ratio for geothermal reservoir exploration in Haute-Sorne, Switzerland

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We reconstruct body waves from seismic ambient noise recorded by a dense seismic temporary nodal network deployed in the Haute-Sorne region, Switzerland. Using the retrieved P-phase arrivals, we conduct 3D seismic tomography to investigate the lithologies and tectonics of the upper crust (i.e. up to around 3 km depth). The network, installed in February 2024 as part of an ongoing Enhanced Geothermal System (EGS) project in Jura Canton, consists of approximately 700 stations with a minimum interstation spacing of around 300 m. Each station continuously recorded one month of seismic ambient noise.

We compute cross-coherency between station pairs in the 0.5–2.5 Hz frequency range to estimate full-tensor Empirical Green's Functions (EGFs). Polarization characteristics are used to separate body waves from surface waves. The imaginary part of the ZR+RZ cross-coherency cancels out Rayleigh wave energy, enabling the reconstruction of P-waves. We compute common-offset bin-stacking with a 100 m bin spacing to improve signal-to-noise ratio. We then filter the dataset by selecting only station pairs with correlation coefficients greater than 0.8 between individual EGFs and the bin-stacked template, leading to the rejection of around 95% of EGFs. This process results in around 15000 high-confidence P-wave arrival times, which we validate against microseismic events near the array.

Finally, we perform 3D P-wave tomography to derive a velocity model, providing detailed information from shallow subsurface structures. We discuss the validity and limitations of comparing this velocity model with the S-wave velocity model and explore the potential of the P-to-S velocity ratio for geothermal reservoir characterization.

# S04 Advancements in observation, processing and interpretation of seismological data

## AS25-0052

## Improving earthquake locations in and surrounding the city of Cartago, Costa Rica, using data from a dense Nodal array

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A dense 3-channel, 70-site, nodal array was installed in and around the city of Cartago, Costa Rica, as part of a joint scientific venture between the Costa Rica Volcanological and Seismological Observatory (OVSICORI-UNA), the United States Geological Survey (USGS), and the Agency for International Development (USAID) to try to locate and characterize faults buried under Quaternary deposits. Moderate magnitude earthquakes destroyed the city of Cartago and killed hundreds of people in the XVIII and XIX centuries, and local faults are likely to produce large earthquakes again in the future. Although microseismicity is frequent in the region, the sparse station spacing of the country-wide seismic network results in a magnitude of completeness higher than M1.5, and location uncertainties greater than 5 km. The resulting resolution has made it difficult to associate events with individual faults, particularly since there are multiples traces mapped of the same fault, and some faults are less than 5 km apart. To overcome this, we operated a nodal array between July 2024 and April 2025, with station density (around 2 km spacing) sufficient to record and locate very small events (some with M<0.0) and with accuracies of hundreds of meters. Here we present a comparison of catalogs derived with data from this deployment and from only OVSICORI-UNA's country-wide permanent network. Preliminary results, from manually located events, indicate that the nodal array catalog has an order of magnitude more earthquakes and that the locations have formal epicentral uncertainties of less than one hundred meters.

## AS25-0114

# THOR: A new SeisComP module for real-time migration-based detection and location of microseismic events

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Real-time microseismic monitoring operations require rapid, reliable and fully automated seismic event detection and location procedures. Conventional algorithms often struggle with high volumes of weak events, especially when events occur in quick succession or have low signal-to-noise ratios. Although full-waveform methods avoid the pitfalls of phase picking and association, their high computational cost and ambiguous event identification criteria limit their real-time applicability. To overcome these challenges, we introduce THOR, a new seiscomp module that synergizes the strengths of classical and full-waveform approaches. THOR is based on the use of either machine learning picks or processed seismic waveforms to perform automated event detection and localization using a migration-based strategy. THOR uses a pre-trained ML model to compute continuous phase probability functions or directly generate non-negative stacking functions from the raw waveforms data. These data (picks or stacking functions) are then back-projected and stacked to simultaneously detect and locate seismic sources in real time. We applied THOR to seismic data from the Hengill geothermal area in Iceland, collected between November 2018 and July 2021 by a dense temporary seismic network. In this time frame more tha 12 thousands earthquake occurred in this region, hence this dataset is an ideal testbed for migration-based detection and localization approaches like THOR. The performance of THOR was validated by comparing its results against seismic catalogs generated using conventional methods, demonstrating its effectiveness for real-time microseismic monitoring.

## AS25-0119

# The OSCARS seismic hazard data products for the Western Gulf of Corinth and the Central Ionian Islands, Greece

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The Open Science Clusters Action for Research and Society (OSCARS) is a Horizon Europe initiative to promote open science by integrating achievements of European Research Infrastructures into sustainable, interdisciplinary, Findable, Accessible, Interoperable, and Reproducible (FAIR) data and services. This study presents seismic hazard data products for two of the most seismically active regions in Greece: the Western Gulf of Corinth and the Central Ionian Islands. These include simulated Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) data for dense grids for return periods of 475 and 950 years, as well as hazard curves and Uniform Hazard Spectra (UHS) for key population centers, all based on the probabilistic method of Cornell and McGuire. These data products use region-specific data, including a Greek earthquake catalogue, which provides seismicity data like the b-value of the Gutenberg–Richter Frequency Magnitude Distribution (FMD), the magnitude of completeness, annual exceedance rates, maximum expected earthquake magnitude, and Ground Motion Prediction Equations (GMPEs) obtained for Greece. A multi-logic tree approach with sub-logic trees for each GMPE was used to reduce epistemic uncertainties, taking into account percentages of normal and non-normal focal mechanisms in each source area to minimize biases in seismotectonic models. Data utilized at the initial compilation level, including source area models from ESHM13 and ESHM20, the earthquake catalogue, GMPEs, and software for simulating PGA, PGV, and UHS, are publicly accessible.

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## AS25-0122

# The complex 2021 Yangbi Earthquake sequence: Evidence of Fluid Involvement

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On 21 May 2021, an $M_W$ 6.1 earthquake struck Yangbi County, Yunnan Province, China, on the southeastern margin of the Tibetan Plateau. This event was preceded by multiple $M_W > 4.0$ foreshocks and followed by an abundant aftershock sequence. Investigating the foreshock triggering process and nucleation dynamics of this earthquake is essential for understanding the mechanisms governing large seismic events and refining hazard mitigation strategies. However, prior studies have yielded divergent interpretations due to variations in datasets and methodologies. Here, we employ a workflow integrating a deep-learning-based phase picker (PhaseNet) and an enhanced GPU-accelerated match-and-locate algorithm (GPU-M&L) to establish a high-precision foreshock catalogue. Analysis of this dataset reveals distinct temporal-spatial evolution across three phases, underscoring the complexity of the nucleation process. Additionally, we identify 116 low-frequency earthquakes whose distribution coincides with fluid channel formation, strongly suggesting that fluid diffusion influenced nucleation. Our findings indicate that the fluid movement is also contributed to the nucleation process except for the aseismic slip process. Several large foreshocks may have broken a fluid reservoir seal, enabling fluid infiltration into pre-existing fault zones and initiating a fluid-driven seismic cascade. As diffusion advanced, previously isolated fault segments interconnected, ultimately facilitating the nucleation of the $M_W$ 6.1 Yangbi earthquake.

## AS25-0125

# Seismic observation and research in the area of China's Great Wall Station in Antarctica

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The Great Wall Seismic Station (CCZ) was established in 1985 and is currently the only permanent seismic station set up by China in the Antarctica. In 2018, the CCZ was renovated by Institute of Geophysics, CEA. After the renovation, the CCZ is equipped with remote monitoring and data transmission capabilities, enabling it to operate stably for long periods without human supervision. This provides high-quality data support for studying the seismic activity characteristics in the South Shetland Islands region where the Great Wall Station is located. This study developed a single-station location method based on machine learning and grid search techniques, applying it to seismic location in the Great Wall Station area, resulting in a seismic distribution map for the South Shetland Islands. The results indicate that earthquakes are primarily distributed along a NE trend in the South Shetland Islands, with volcanic earthquake clusters found in the Bransfield Strait. Additionally, several intermediate-depth earthquakes exceeding 100 km were recorded near the fore-arc region of the South Shetland Trench and around the South Shetland Islands, providing direct seismic evidence that the Phoenix Plate is still undergoing subduction beneath the South Shetland Trench. This provides direct seismic evidence that the subduction of the Phoenix Plate beneath the South Shetland Trench is still ongoing.

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## AS25-0136

# A new characteristic function for DFOS data signal enhancement

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Distributed Fiber Optic Sensing (DFOS) is now becoming widely employed in microseismic monitoring applications, as a complement to traditional seismic networks. However, DFOS data are inherently noisier due to fiber coupling issues and optical noise, and generally need advanced signal processing techniques. Until now several denoising methods have been widely explored (mainly machine learning-based), while the use of characteristic functions (CFs) for improving the signal-to-noise ratio (SNR) in DFOS data remains largely underexplored.

This study introduces a novel hyperbolic cosine-based CF and evaluates its effectiveness in enhancing the SNR of DFOS recordings. We compare its performance against standard CFs such as STA/LTA and kurtosis. The analysis follows a two-step approach: first, we quantify the SNR improvements in preprocessed DFOS data, and second, we assess the coherence enhancement across fiber channels using a semblance-based detector.

We apply this methodology to both synthetic datasets and real seismic data from the FORGE geothermal site in Utah, USA, analyzing 947 recorded events, and data collected in the Pyrenees. Our results demonstrate that the hyperbolic cosine-based CF significantly improves SNR and signal coherence, outperforming conventional methods in certain scenarios. Additionally, computational efficiency analysis confirms its feasibility for large-scale seismic monitoring applications.

We would like to thank Total Energies for sharing the Pyrenees data set with us, as well as Febus Optic for providing the DAS interrogator used for the data acquisition.

## AS25-0363

# A spectral subtraction-based method for enhancing Distributed Fiber Optic Sensing data

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Recent advances in Distributed Fiber Optic Sensing (DFOS) technology have highlighted its potential in seismological applications. By converting standard fiber-optic cables into dense arrays of seismic sensors, DFOS systems offer unique advantages for microseismic monitoring, particularly in complex environments such as deep boreholes used in Enhanced Geothermal Systems (EGS) or Carbon Capture and Storage (CCS) operations, where conventional seismic sensors face limitations.

However, seismic waveforms recorded by fiber-optic sensors typically exhibit lower Signal-to-Noise Ratio (SNR) values compared to traditional seismometers. The high spatial and temporal resolution of DFOS arrays present numerous opportunities for developing new processing techniques to address this issue, as conventional filtering methods often struggle to recover information of the seismic wavefield, especially from DFOS recordings characterized by a low SNR.

This research introduces a robust denoising methodology based on spectral subtraction algorithms, commonly used in speech processing, to improve the SNR of microseismic data and improve the detection of low-SNR seismic events. The approach is initially tested on synthetic DFOS data, replicating realistic acquisition geometries and noise environments from the Utah FORGE EGS site. It is then applied to actual DFOS data collected during the April 2022 stimulation operations at FORGE under varying SNR conditions. Results from both synthetic and real DFOS recordings show significant improvements in SNR across different noise conditions. The proposed spectral subtraction-based denoising workflow demonstrates strong performance compared to traditional filtering techniques, offering a simple yet effective solution for enhancing seismic signals recorded by DFOS systems.

## AS25-0364

# LION: Location by waveform-stacking with Integrated fiber Optic and seismometer Networks

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Distributed Fiber-Optic Sensing (DFOS) technologies provide meter-scale resolution of the seismic wavefield. DFOS systems can augment the coverage of traditional sensors, contributing to the next generation of integrated seismic networks. However, DFOS effectiveness may be hindered by limited azimuthal coverage, directional sensitivity, and noise sources such as optical noise and cable coupling inhomogeneities. These factors complicate the application of standard, single sensor-based seismic monitoring routines for event location.

Waveform stacking along predicted travel-times offers an alternative approach for event location, particularly advantageous for dense networks, thus ideal for DFOS systems. However, the need for 3D travel-time lookup tables for each sensor can make waveform stacking-based methods computationally intensive for DFOS technologies. A simple and efficient solution is reducing the dimensionality of the travel-time lookup tables, which is justified by the typical lack of detailed 3D velocity models and the demands of real-time monitoring.

Here, we present LION, a coherence-based earthquake locator designed to efficiently integrate DFOS and conventional seismic sensors for near real-time analysis. By assuming cylindrical symmetry in the velocity model, LION uses a single 2D traveltime lookup table for all sensors, stacking waveforms to generate coherence maps for (a) the seismometer network, (b) the optical fiber, and (c) the integrated network. The proposed approach ensures both the separation of event location workflows for DFOS and seismometer networks and the production of a balanced, final integrated coherence map. We show LION's performance on hybrid onshore and offshore networks, including automatic data selection to reduce DFOS redundancy.

## AS25-0426

# Understanding the stress state based on temporal changes in the activity of small to mid-sized earthquakes with DEFS

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We examined the deviatoric stress magnitude in the crust, based on the temporal changes in seismic activity of events between the pre- and post-seismic period of the 2016 Kumamoto earthquake, Japan. Firstly, we computed temporal changes in Energetics-based Failure Stress (DEFS) caused by the mainshock, under the stress models with different effective friction coefficients, m' (Terakawa et al., 2020, 2025). Unlike DCFS, the spatial distribution of DEFS depends on the assumed effective friction coefficient, or the deviatoric stress magnitude of stress fields. The dependence became remarkable within the source region, wheras it became less remarkable in the regions farther from the source region. We expect the increase in seismic activity in the source region in the stress model with small effective friction coefficients (m'< 0.1). Conversely, we expect the decrease in seismic activity in the stress model with larger effective friction coefficients. In evaluating the temporal changes in seismicity, we should pay attention to the fact that earthquakes are not only controlled by stress but also by pore-fluid pressure. Since it is not realistic to correctly evaluate changes in pore-fluid pressure, we focus on the effects of stress on temporal changes in seismicity. We classified events into single events, mainshocks, aftershocks and foreshocks, using the technique of cluster analysis (Zaliapin and Ben-Zion, 2013). Since foreshocks and aftershocks are often reported to be triggered by fluids, we targeted only single events and mainshocks for the analysis. Comparing the theoretical and observed temporal changes in seismicity, we will discuss the stress state.

## AS25-0448

# Enhanced real-time estimation of seismic source rupture characteristics via P-wave early warning parameters

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The integration of real-time seismic source rupture characteristic estimation into earthquake early warning systems (EEWS) can significantly enhance disaster mitigation efforts. Traditional point-source models, ignoring rupture propagation complexities, often yield inaccurate warning intensity and damage zones. Existing methods, typically delayed by minutes, fail to meet the stringent timeliness requirements of EEWS. In this study, we present an improved real-time method for continuous rupture characteristic estimation, incorporating P-wave parameters to refine the finite rupture template matching approach, known as FinDer.

Systematic tests indicate that this method provides results about 3 seconds faster than FinDer at the same post-earthquake moment, with certain cases showing a 5-second improvement. Such speed enhancements are crucial for effective early warning, enabling more timely responses and greater disaster mitigation. In the early rupture stages, the estimated strike $\theta$ varies significantly due to diverse seismic radiation patterns, site conditions, and propagation path effects. However, $\theta$ gradually stabilizes as the rupture progresses and more data is available. For earthquakes below M7.0, stable rupture parameters typically emerge 6–10 s after the earthquake origin. In contrast, larger earthquakes, especially mega-events like the M8.0 Wenchuan quake, require longer periods for results to stabilize, around 40 seconds after the origin in areas with relatively sparse station coverage.

This refined method enhances the precision and responsiveness of EEWS, offering a more reliable tool for seismic hazard assessment and mitigation. It is especially valuable in scenarios where rapid, accurate information is vital for minimizing potential damage and saving lives.

## AS25-0465

# Extraction of ground vibration information from earthquake monitoring videos based on computer vision

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Most strong motion seismic stations are established in remote areas far from densely populated areas. In densely populated urban areas, there are often no ideal conditions for setting up enough and densely packed stations. However, surveillance cameras are widely deployed in urban areas, which can record valuable video vibration data during a strong earthquake occurs. With the help of rapidly developing artificial intelligence target tracking technology in computer vision, we have developed a new method to automatically extract seismic signals from vibration videos. Taking the monitoring video of 2022 M 6.8 Luding earthquake as an example, first prepare and select key points in the video, then we apply Cotracker, a well trained automatic target tracking model to capture the future motion trajectory of the key point in the current image, then we calculate the relative displacement of the trajectory over time. Finally, we compare the accuqired displacement data quantitatively and qualitatively with the nearby strong motion seismic data. The results show that compared with strong earthquake records, video vibration not only has a high correlation and consistency in waveform, but also can obtain relatively accurate and clear P and S arrival time information,which can be used as a very meaningful supplement to the relatively sparse strong ground motion records. Our study demonstrates the potential application of video tracking technology in seismological applications, and is expected to provide rich information for strong earthquake monitoring in densely populated areas, helping enhance earthquake emergency management and earthquake post-disaster assessment ability.

## AS25-0475

# Mitigation of Disturbances in Apollo Lunar Seismic Data and Primary Findings in the Search for Long-Period Signals

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Planetary seismic data are crucial for studying planetary interiors, yet acquiring high-quality recordings in harsh extraterrestrial environments is far more challenging than on Earth. Both the Apollo Passive Seismic Experiment on the Moon and the Seismic Experiment for Interior Structure on Mars face significant transient disturbances across a wide range of frequencies, complicating the search for valuable long-period signals related to planetary free oscillations and gravitational wave responses. To address this challenge, we propose an automated workflow that leverages deep learning to detect and remove strong transient disturbances in Apollo seismic data, thereby enhancing the recovery of weak long-period signals. We evaluated two approaches for disturbance removal: one that directly mutes transient segments before applying Fourier transforms, and another that treats these segments as data gaps and utilizes the Lomb–Scargle periodogram. Synthetic tests demonstrate that even when ~80% of the data is contaminated, most low-frequency peaks can still be recovered. For disturbance detection, we first developed a manual annotation tool and then trained a deep learning model using manually labeled data. Our model successfully recovers the recently discovered temperature-related long-period signals in Apollo data without relying on stacking or clustering techniques, highlighting its potential for re-examining the long-period signals in Apollo seismic records. Subsequently, we applied the method to perform a preliminary scan of all Apollo lunar seismic data and constructed a catalog of the long-period signal distribution, with further research needed to characterize and assess the features and significance of the long-period signals in this catalog.

## AS25-0478

# Confident Learning for efficient seismic dataset cleaning and accurate earthquake monitoring

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The exponential expansion of seismic observations worldwide has resulted in extensive seismic data volumes that beyond the capacity of processing routines performed manually by seismologists, necessitating the development AI-based processing methods. Despite that AI-based methods can detect much more earthquakes compared to previous manual practice and reveal fine-scale patterns, these results are often of relatively high error and uncertainty when compared to manually annotated catalog. This issue can trace directly to data quality challenges in current large seismic datasets, including label noise caused by subjective annotator interpretations among different annotators and semi-automated workflows, coupled with imbalanced data distribution across diverse scenarios. While recent datasets like CREW have pioneered quality-controlled curation, large legacy datasets such as STEAD, INSTANCE, DiTing, MLAAPDE, and Seis-PnSn lack label quality control. Besides, strategies for addressing the imbalanced seismic data distribution (e.g., epicenter distance, magnitude, signal-to-noise ratio) are poorly understood. Inspired by advances in Data-Centric AI, where systematic dataset refinement drives model improvement, we implement confident learning to evaluate and improve these legacy datasets. First, a self-supervised pre-trained model extracts context-aware seismic features, generating probabilistic predictions and confidence distributions. Second, a Bayesian analyzer systematically quantifies distributional biases between model predictions and expert-derived annotations, probabilistically characterizing label noise distributions to detect mislabeled events in datasets. The effects of sample distributions are also studied. The retrained deep learning model on the refined sub-datasets exhibits reductions in errors and fewer false detections. Thus, our study can contribute to improving seismic dataset quality and seismic monitoring accuracy.

## AS25-0495

# PYROS: A Python framework for modeling DAS data

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The advent of fiber optics technology, specifically Distributed Acoustic Sensing (DAS), is revolutionizing seismic data acquisition in seismology. DAS is increasingly used for various applications, such as passive seismic imaging, analyzing natural and induced seismic sequences, and microseismic monitoring in Enhanced Geothermal Systems (EGS) and Carbon Capture Storage (CCS) operations. Its main advantage is the ability to collect data in logistically challenging locations, like volcanic or offshore areas, and extreme environments, such as deep geothermal boreholes, where conventional seismic sensors are inadequate. Despite its potential, DAS technology presents challenges, primarily the massive data volumes generated, which hinder existing storage and analysis systems. Consequently, the availability of public datasets is limited compared to traditional seismological data, impeding the development of analysis methodologies tailored to DAS data characteristics. To tackle this issue, we propose a methodology within the Pyrocko framework to generate synthetic DAS data. These synthetic datasets are crucial not only for benchmarking new analysis techniques but also for implementing full-waveform inversion methods for characterizing seismic sources. Our approach adapts the reflectivity method, like QSEIS, for generating 1D Green's functions, allowing us to create synthetic strain or strain-rate traces that simulate DAS acquisition across different geometries. We validate our results by comparing them with synthetics generated by commercial software and with real data from boreholes in EGS and CCS contexts. To enhance realism, we stochastically simulate and incorporate DAS noise characteristics into the synthetic traces.

## AS25-0529

# AI-Driven Earthquake Detection and High-Resolution Relocation: Insights into the 2025 Santorini—Amorgos Seismic Swarm and Fluid-Induced Genesis

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The seismic crisis in the South Aegean Sea, between the islands of Santorini and Amorgos, Greece, began in September 2024 with a magmatic inflation at shallow depth beneath the Santorini caldera, detected by GPS, and minor seismicity. Activity escalated with an intense seismic swarm, in the lower crust, northeast of Santorini, on January 26, 2025, propagating into shallower crustal depths across a network of active faults. To investigate the swarm, we apply machine learning and high-resolution relocation techniques. Continuous waveform data from seismic stations within a 200 km radius are analyzed, with P- and S-wave arrivals automatically picked using PhaseNet. Event associations are performed using GENIE, a graph neural network-based algorithm, and GaMMA, a Bayesian Gaussian Mixture Model associator, for comparative evaluation. Events are initially located with NonLinLoc and subsequently refined with hypoDD, while assessing the sensitivity of results to various velocity models. Our analysis aims to characterize the swarm's duration, recurrence intervals, clustering behavior, and the temporal evolution of its magnitude and depth distributions. Preliminary tensor solutions reveal positive isotropic components, indicating volumetric expansion, commonly linked to fluid migration. We further assess this hypothesis by integrating seismic and geodetic data to evaluate the role of fluids in fault reactivation and stress redistribution. Our objective is to establish a standardized workflow for high-resolution seismic monitoring, applicable to other environments and application scopes, aiming to enhance real-time hazard assessment for fluid-active fault systems, with direct implications for $CO_2$ storage, geothermal energy, and subsurface operations.

## AS25-0545

# Can temporally and spatially varying b-values improve earthquake forecasting? Insights from a machine-learning-enhanced catalog in central Italy

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The b-value of the Gutenberg-Richter law is crucial for modern hazard models and seismicity forecasting. For a robust b-value estimate, a sufficiently large number of earthquakes are necessary. At the same time, a growing number of studies suggests that the b-value changes with factors such as time (Gulia et al., 2018), differential stress (Scholz, 2015), and thermal regime (Nishikawa and Ide, 2014). Thus, there is a trade-off between using enough data and accounting for b-value changes. The recently introduced b-significant method (Mirwald et al., 2024)addressed this problem and offers a way to find the optimal number of earthquakes.

In this work, we test if using such an optimal strategy can improve our forecasting abilities. We leverage a machine-learning-enhanced earthquake catalog in Central Italy containing >900 k events (Tan et al., 2021). This allows us to analyze finer-grained b-value variations than traditional catalogs, capturing their spatiotemporal complexity (Herrmann et al., 2022). Specifically, we first estimate the optimal temporal, spatial, and combined spatiotemporal scales for forecasting future seismicity using the first half of the dataset. Using the second half of the dataset, we then assess pseudoprospectively if a varying b-value, estimated with the parameters obtained in the first step, results in a positive information gain. Finally, we map regions where b-values change most significantly and interpret potential physical mechanisms driving these variations.

Our findings will contribute to a better understanding of how variations in b-values can be leveraged for earthquake forecasting when high-resolution machine-learning-enhanced catalogs are available.

## AS25-0565

# Analysing seismic node and dark-fibre DAS data from Costa Rican volcanoes using deep learning processing methods

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The emergence of low-cost dense acquisition technologies, such as fibre-optic sensing and battery-powered nodes, has clear potential to revolutionise real-time seismic monitoring and seismic imaging capabilities. However, the integration of these technologies with existing regional networks and signal processing workflows (e.g., deep learning phase arrival detection) remains at a nascent stage. Using data acquired during short-term seismic node and dark-fibre DAS deployments at Rincón de la Vieja and Miravalles volcanoes in Costa Rica, we assess a variety of deep learning models and strategies for effective and efficient signal processing on these differing data types. To mitigate the increased noise levels of these low-cost sensor technologies, a weakly-supervised learning approach is taken to greatly suppress incoherent random noise on both DAS and node data without the need for any 'clean' training examples. A comparison of several off-the-shelf and newly-trained phase arrival detection models is then undertaken to identify optimal models/strategies for detecting volcanic seismicity across instrument types. We find that the best-performing models increase the number of detected events by more than a factor of 50 when incorporating data from these short-term deployments, as opposed to using sensor data from the existing regional broadband network alone. Combined with retroactive analysis (e.g., waveform similarity and relative relocation techniques), the heightened level of detection, denser sampling of seismicity, and lower-error hypocenter estimates provide the opportunity to better understand these poorly studied volcanic systems, which are subject to frequent eruptions and seismic swarms, and host economically important geothermal and clean energy infrastructure.

## AS25-0600

# Virtual Seismic Arrays: towards wavefield prediction for next-generation gravitational wave detectors

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As gravitational wave detections achieve unprecedented sensitivity, mitigating seismic noise becomes increasingly critical. We propose an innovative wavefield prediction approach based on machine learning, aimed at revolutionizing noise reduction strategies for next-generation gravitational wave observatories such as the Einstein Telescope. By training encoder-decoder networks, we can model and predict seismic wave propagation across a sensor array using data from a single reference station, after the other array stations have been removed. This method enables precise forecasting of vibrations, facilitating adaptive systems to effectively counteract potential interferences with detector operations. We present a proof-of-concept for a functioning Virtual Seismic Array, which accurately predicts the microseism noise wavefield across the Gräfenberg array in Germany from a single array station. Our findings underscore the potential of this technique as a foundational technology for upcoming generations of gravitational wave detectors, marking a significant advance towards unveiling deeper cosmic insights.

## AS25-0661

# Evaluation of Site Amplification correction techniques for ground motion to determine the seismic intensity from borehole seismic data

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The ground motion of an earthquake felt by humans on the surface or in buildings occurs as a convolution of the earthquake source, path effect, and site effect. Even in areas located at the same distance from the epicenter, ground motion may vary depending on the characteristics of the site. Therefore, it is necessary to understand the geological characteristics of the station area and to analyze the effect of site-specific conditions from seismic data. Currently, KMA calculates PGA from surface and borehole seismic data and produces a seismic intensity map using Shakemap 3.5 and Borcherdt (1994) methods to inform the public about earthquake impacts. To correct seismic data from borehole to surface level, KMA uses amplification factors from Borcherdt (1994). However, these factors, based on western U.S. data, may not accurately reflect the regional characteristics of the Korean Peninsula. To address this, site amplification coefficients were developed using PySeismoSoil for each grid, based on borehole data and geological profiles(KMA, 2024). We developed a method to evaluate ground correction techniques considering soil amplification effects from borehole depths. For direct comparison, ten borehole stations were selected based on soil type, and temporary surface seismometers were installed. To evaluate the techniques, 34 earthquakes with local magnitude of 2.0 or greater, including Buan earthquake (ML 4.8), from November 2023 to January 2025, were analyzed. Using actual surface records as references, we verified the validity of current correction techniques (Borcherdt, 1994), and site amplification coefficients through comparisons of amplitudes ratios(Lai et al., 2022) and residuals.

## AS25-0698

# A high-resolution earthquake catalogue from a nodal deployment in Lago, Tuscany, Italy

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Understanding the spatial distribution of seismicity is key to investigate nucleation processes and kinematics of earthquakes occurring in tectonically active settings. Seismic sequences in the Larderello-Travale Geothermal Field, Italy are typically associated with high-enthalpy geothermal fluids. In this work we investigate the role of the microseismicity of the Lago area and its potential correlation with local tectonic and magmatic features suggested in previous structural studies.

We derive a high-resolution catalogue of earthquake hypocenters and magnitudes from a seismic nodal network consisting of 225 short period sensors deployed in an area of 18x18 km around the region of Lago Boracifero, Tuscany, in the framework of the project "Multidisciplinary and InteGRated Approach for geoThermal Exploration" (MIGRATE), during a period of one month starting in September 2024. We obtained a preliminary earthquake catalogue of around 300 events within the nodal network derived from nearly 70 thousand seismic phases successfully associated with Pyocto and located with NonLinLoc. From our preliminary observations, we found a cluster of around 50 events at 3 km depth south of the network and a deeper cluster of nearly 80 events out of the network coverage.

We leverage the high density of stations in our temporal network by applying waveform-based methods to improve the detection and location accuracy of microseismicity in our dataset, dominated by low signal-to-noise ratio conditions. Further steps involve the source analysis of the events in the catalogue and its potential relation to fluid-driven seismic sequences.

## AS25-0724

# Exploring the Capabilities of Deep Learning-Enhanced Waveform Stacking in Local Seismic Monitoring

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The 2024 Muswellbrook earthquake sequence in New South Wales, Australia, began on 23 August 2024 with an ML 4.7 earthquake near the Mount Arthur Coal Mine. This was followed by an ML 4.4 event on 24 August, an ML 4.5 earthquake on 7 September, and an ML 4.1 earthquake on 12 November (Allen, 2024). Seismic activity in this region, part of the Hunter Valley, is influenced by both tectonic processes and mining operations. The Hunter Valley has a long history of seismicity, with the 1989 ML 5.6 Newcastle earthquake being the most destructive (Clark, 2010). To enhance seismic monitoring, Geoscience Australia deployed temporary seismic stations in the epicentral region. These stations, along with national broadband stations and the RaspberryShake community network, were processed using THOR, an automated waveform stacking-based localization method that integrates deep learning-driven phase detection, significantly improving event detection and location accuracy. THOR was tested using data from all three station types, enabling a high-resolution analysis of the sequence. The epicentral region spanned 60×40 km, with heterogeneous station coverage and interstation distances ranging from 2 km to 330 km. For event localization, PhaseNet was used to generate confidence curves, which were stacked at each grid node. The final event locations were determined by identifying the maximum coherence across the grid. Results show that THOR effectively detects and accurately localizes seismic events, even in low-magnitude and sparse station coverage settings. The method performs robustly in both real-time and offline processing, making it a valuable tool for local seismic monitoring.

## AS25-0828

# Seismotectonic analysis and definition of seismicity zones of Cameroon

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A compilation of databases from Cameroon and neighbourings countries is carried out including seismicity, stress tensor distribution, gravity, magnetic, topography, lithosphere structure and geological data. Guidelines for the preparation of seismotectonic map and associated data analysis are used to create a consistent database and results across the study area. An important step was to produce a homogeneous catalogue of seismicity. Fault plane solutions and stress information were obtained from literature and international organisation databases. Many faults were identified, possibly active though some of them were not associated with significant seismicity. The seismotectonic model for Cameroon was then built from a classification of faults, neotectonic and seismogenic regions. This well structured and highly data-driven approach has been developed specifically for the definition of seismic source zones. The results of the seismotectonic analysis allowed characterizing seventeen seismotectonic units in Cameroon. Five source zones are defined in the Mt Cameroon region which represents the greatest seismicity activity in the study area. The crustal thickness map of Cameroon reveals at the conctat zone between the thicknened Congo craton and the thinned Pan-African belt is favourable for the developpement of megastructures such as Central Cameroon shear zone (including Foumban-Bankim, Mbéré-Djérem and Meiganga shear zones), and Nyong unit shear zones (Kribi-Campo and Djabilobé shear zones). This region represents the second highest seismicity zone and carries five source zones. The heterogeneity of lithospheric materials and the structural deformations within the Central African Orogenic Belt make it a seismogenic domainwhich are subdivised into sources zones.

## AS25-0847

# Real-time monitoring through passive seismic interferometry: feasibility and limitations from the 2024 Greek seismic swarm case study

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Passive Seismic interferometry is an effective tool for detecting minute changes in crustal seismic wave velocity, making it highly sensitive to variations induced by tectonic activity, volcanic processes, or environmental factors. This technique has been widely applied to monitor seismically active regions, volcanic areas, and crustal elastic parameter variations over time. However, its implementation remains strongly user-dependent, requiring careful tuning of multiple processing parameters, which can significantly influence the results. In this study, we assess the feasibility of real-time monitoring using passive seismic interferometry, evaluating its potential drawbacks and limitations. We focus on the 2024 Greek seismic swarm, a highly active sequence that provides an ideal test case for investigating the method's effectiveness in tracking transient velocity changes. Our analysis explores the impact of parameter selection, computational constraints, and results quality on a nearly real-time application. Our aim is to provide insights into the robustness and reliability of passive seismic interferometry for real-time seismic monitoring, by constraining as many processing parameters as possible or providing the user with suggested values. Our results will contribute to optimizing parameter selection and improving automation strategies, ultimately enhancing the applicability of this method for (near-)real-time assessment of seismic, volcanic and environmental changes.

## AS25-0859

# Benchmarking phase picks from deep learning algorithms using the ISC Bulletin

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In the application of deep learning techniques to seismology a notable success has been the progress in automating seismic phase detection. This has resulted in the development of many deep learning models and training datasets, and a proliferation of users applying these emerging techniques. There have been some recent attempts at benchmarking the performance of deep learning algorithms for phase picking. These studies have focused on evaluating the performance of these models on selected high quality data. The relative impact of the chosen data sample rate and filtering applied to the data is a known issue and is currently under-investigated. Here we will benchmark the leading deep learning models against both local, regional and teleseismic picks reported to the International Seismological Centre (ISC) and local manual phase picking performed at the ISC. We intend to evaluate these algorithms against data of variable quality to investigate the viability of the use of unsupervised phase picking with deep learning algorithms. Further we will focus on quantifying the effect that varying the filtering and sample rate of the data has on the number of picks identified, their confidence and accuracy. In order to place these results in context we will also assess the performance of globally reporting agencies, utilising events and stations reported by multiple agencies. In this we hope to provide and extend a global baseline for evaluating the performance of deep learning phase picking algorithms, relative to the inherent variation in picks reported to the ISC.

## AS25-0879

# Back-projection Processing of Taiwan's Dense Strong Motion Network for Rapid Earthquake Hypocenter Determination

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The Taiwan Strong Motion Instrumentation Program (TSMIP) consists of a network of strong-motion stations uniformly distributed across Taiwan. This network is designed to collect seismic waveforms to support seismological research and seismic hazard assessment. In recent years, TSMIP stations have been upgraded for real-time recording via internet connections, enabling the rapid generation of intensity reports for each county following significant earthquakes. In this study, we present an automated method for processing data from this dense strong-motion network. Using a back-projection (BP) approach, we determine the hypocenter location of an earthquake and estimate its focal mechanism by waveform stacking. Additionally, an Automatic Gain Control (AGC) method has been employed to enhance weak signals, allowing for the detection of hidden events within an earthquake sequence. We have developed a new algorithm capable of near real-time event relocation and focal mechanism determination over a wide magnitude range. We applied this method to analyze the first 30 minutes of aftershocks following the **September 17, 2022, ML 6.4 Guanshan, Taiwan earthquake,** as well as to relocate events from the **January 20, 2025, ML 6.4 Dapu, Taiwan earthquake sequence.** Our approach effectively utilizes waveform stacking techniques to improve event localization and focal mechanism estimation. The findings contribute to a deeper understanding of earthquake processes and have the potential to enhance seismic monitoring strategies for future large-scale events. However, compared to traditional methods, certain limitations remain. Based on our findings, we provide recommendations for further improvements and refinements in this report.

## AS25-0958

# EqLocOptimizer: A tool for evaluating best input parameters of earthquake location programs based on events quality criteria

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Accurate earthquake location is critical for studying seismicity, tectonic processes, and hazard assessment. The precision of earthquake locations depends on various factors, including seismic phase arrivals, velocity models, and the selection of input parameters in location programs. However, choosing optimal input parameters is often a manual, time-consuming process with no standardized framework. EqLocOptimizer is introduced as an automated, algorithm-agnostic tool designed to optimize input parameters for earthquake location programs based on event quality criteria. By using Optuna, a modern hyperparameter optimization framework, EqLocOptimizer systematically evaluates and selects parameters to enhance earthquake location accuracy. The tool minimizes reliance on subjective decisions and improves reproducibility by considering key metrics such as arrival-times RMS, horizontal and depth errors, and the number of high-quality events. The optimization workflow involves defining parameters search space, running earthquake location trials, evaluating results based on objective functions, and refining parameters iteratively. The tool can provide such as optimization history and parameter importance plots, help analyze the influence of different parameters on location accuracy. To demonstrate its effectiveness, we applied EqLocOptimizer to three widely used location programs: Hypo71, HypoDD, and NonLinLoc, using a real-word data from the Ahar-Varzaghan aftershock sequence in NW Iran. Results showed a significant improvement in earthquake locations, reducing uncertainties (~ 10%–~30%) and increasing the number of high-quality events compared to default parameter settings (~20%). EqLocOptimizer provides a systematic and efficient approach to earthquake location parameter tuning, making it a valuable tool for seismologists aiming to improve earthquake catalogs and enhance seismic hazard assessment.

## AS25-0980

# Güralp Artius—A novel triaxial broadband node designed for Large-N arrays

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The Artius broadband node represents transformative innovation in seismic instrumentation, designed to bridge the gap between traditional broadband seismometers and popular nodal systems. While broadband seismometers offer unparalleled sensitivity and frequency range, their cost and complexity often limit large-scale and dense deployments. Conversely, geophones provide cost-effective solutions for high-frequency applications but lack sensitivity to low-frequency seismic signals, which are critical for many research and monitoring purposes. Artius provides a cost-effective compromise, delivering increased sensitivity and a true broadband frequency range at an economic price point.

Artius integrates a compact, highly sensitive broadband seismometer within an environmentally sealed anodized aluminium enclosure, ensuring optimal performance and robustness across diverse geophysical applications. Artius' response of 30 seconds to 200 Hz, vastly outperforms geophone-based systems while remaining suited to rapid, temporary deployments. The small unit can be pushed or staked into the ground and connected to an external power supply. Artius offers real time data monitoring, as well as passive data collection and features an onboard SEEDlink server, for compatibility with standard seismological monitoring techniques.

Artius is designed to be connected into an eight-node capacity docking station for data validation, mass data download plus configuration and testing prior to deployment. Artius nodes are intended to deploy in large arrays for passive seismology, ambient noise studies, and earthquake studies. Compatible with Artius is Discovery, an advanced software platform for seismic data acquisition, processing, and analysis. Discovery was designed to handle large datasets and integrates seamlessly with Artius, supporting both offline playback and real-time data analysis.

## AS25-0982

# Automated Focal Mechanism Computation for Small-Magnitude Earthquakes in Northeastern Italy

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Understanding earthquake mechanics and stress distribution is crucial in seismically active regions like the Southeastern Alps. This study presents an automated workflow for focal mechanism computation, integrating deep learning-based polarity picking with advanced focal mechanism determination methods.

We applied this approach to 70 earthquakes (Md 2.2–3.6) from 2014–2023 in northeastern Italy, using manually picked polarities as a benchmark. Our workflow leverages the Convolutional First Motion (CFM) neural network for polarity classification and SKHASH, a grid-search-based method for focal mechanism computation. CFM, trained on over 140,000 waveforms, achieved >96% accuracy on independent datasets and showed 97% agreement with manual classifications in our study area. SKHASH refines focal mechanisms by incorporating uncertainty modeling and machine-learning-derived inputs, improving accuracy for small-magnitude events.

We validated our method against existing catalogues and computed 26 new focal mechanisms (Md ≥ 2.3) for 2024, demonstrating the feasibility of near real-time focal mechanism determination. The results confirm the potential of integrating AI-driven tools with advanced seismological methods to improve earthquake characterization in densely monitored regions. The updated catalogue provides valuable insights into regional stress distribution and fault dynamics, offering a robust framework for future seismic hazard assessments.

## AS25-1007

# Evaluating the Performance of Machine-Learning-Based Phase Pickers for Crustal and Intermediate-Depth Earthquakes in Romania

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Seismic activity in Romania spans a range of tectonic environments, from crustal faults to intermediate-depth events in the Vrancea seismic zone, the latter being the primary source of seismic hazard in the country. This activity is continuously monitored by a network of over 140 seismic stations, generating a large volume of data. As the volume of continuous data grows, it places an increasing demand on analysts responsible for maintaining and updating the revised seismic catalog.

Recently developed machine-learning tools for seismic phase picking and event association have proven to be highly effective in processing large volumes of seismological data, enabling rapid and accurate automated event detection. As a result, many seismological observatories and data centers are integrating these tools into their routine processing workflows to enhance the quality of their seismic catalogs, particularly by improving the detection of low-magnitude events.

In this study, we explore the potential of machine-learning-based phase pickers, with a primary focus on the PhaseNet picker, for detecting phase arrivals from intermediate-depth and crustal earthquakes in Romania. We use data from events in the Vrancea seismic zone and a recent crustal sequence as case studies. To assess PhaseNet's performance, we compare its phase picks with manually revised picks from seismic bulletins spanning the period 2014–2024. This comparison helps us evaluate the applicability of the existing PhaseNet model and determine whether retraining is necessary. Additionally, we examine how machine-learning-based processing can be integrated into the routine analysis at the Romanian Seismological Data Centre to enhance seismic monitoring capabilities.

## AS25-1035

# Seismic Catalog Update for mainland France: AI-Enhanced Analysis and Catalog Merging from 2010 to 2018

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This work updates the seismic catalog of mainland France for the period 2010–2018, continuing the efforts of the SI-Hex project, which covered 1962–2009. During this time, seismic monitoring capabilities were significantly enhanced with the deployment of broadband stations under the Epos-France research infrastructure, as well as several temporary networks. These improvements have greatly increased the amount of detections and seismic events to process.

This new catalog benefits from artificial intelligence to refine event detection and classification. It uses Seisbench/PhaseNet for automatic phase picking and deep learning CNN to distinguish between earthquakes, quarry blasts and explosions. The dataset incorporates manual picks from BCSF-Renass, CEA/LDG, regional observatories, as well as automatic picks from Epos-France stations and neighboring countries. These were obtained using a PhaseNet model trained on BCSF-Renass manual picks from 2016 to 2023.

The workflow involves clustering picks to reduce computational cost, associating seismic phase picks to create events using HDBSCAN and PyOcto, locating events with NonLinLoc, and computing moment magnitude (Mw) using a modified SourceSpec. Magnitude station corrections enhance reliability, especially for low-magnitude events. A deep learning CNN, trained on the BCSF-Renass catalog from 2021 to 2022, discriminates between earthquakes and quarry blasts.

This final catalog provides an updated view of France's seismicity from 2010 to 2018. It is characterised by an increase in the detection level of low-magnitude events, an improved classification, and more precise magnitude estimates, highlighting the benefits of AI-driven seismic monitoring.

## AS25-1048

# Improving the precision of global earthquake locations using incidental seismic arrays

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In recent years there has been a proliferation of seismic sensors, concentrated in high-quality seismic networks in many areas of the globe. The workload associated with picking the increasing number of stations means many reporters choose to report tele-seismic phase picks at a subset of stations. Additionally, the signal to noise characteristics of other stations may make tele-seismic reporting impractical. To make the best use of the densely concentrated seismic networks, we use local and regional seismic networks to form 'incidental' seismic arrays, where the stacked signals can improve the detection of tele-seismic phases. These incidental arrays are formed where there are 10 or more broadband seismic stations within a 200 km by 200 km region. We optimise the selection of stations to form a global set of incidental arrays. For each array we calculate a Vespagram on an optimised back azimuth, for a range of slowness values. This allows the direct P phase arrival and other phases with similar ray paths, such as depth phases, to be more clearly identified. Previous studies have shown that these incidental arrays can provide reliable depth phase measurements, that can add depth resolution to remote intermediate depth and deep earthquakes. Here we show that these incidental arrays can also be used to improve the azimuthal coverage for remote earthquakes, and therefore provide an opportunity to improve the location quality of remote earthquakes that are only reported by global earthquake monitoring agencies (e.g. NEIC, GFZ, IDC).

## AS25-1077

# Monitoring induced seismicity in northern Alsace (France) with the contribution of "SeismoCitizen" Raspberry Shake dense network

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The PrESENCE ANR research project (2022–2026) focuses on seismic hazards induced by deep geothermal activities in northern Alsace, northeastern France, and their associated societal perception. The project utilizes a dense network of low-cost, internet-connected, Raspberry Shake seismic stations to enhance seismic monitoring. These stations are deployed in residences and administrative buildings of volunteer citizens and authorities. They complement the French permanent seismic network. The primary goal is to improve the detection and location of seismic events, particularly small ones, in areas where deep geothermal operations occur such as Soultz-sous-Forêts and Rittershoffen.

The network's topology was determined by the location of permanent public stations, geothermal power plants, volunteer hosts and the availability of low-cost stations. Currently, 34 stations are operational in northern Alsace. The project builds on our past experiences deploying similar networks in north-east France and Mayotte, ensuring reliable data acquisition via direct station connections using the Seedlink protocol over VPN, complemented by hardware watchdogs. The configuration and management of Raspberry Shake stations are handled using Ansible, an open-source IT automation platform..

Based on this denser network, the seismicity catalog workflow integrates artificial intelligence tools such as Seisbench/PhaseNet for automatic phase picking and deep learning methods to distinguish between earthquakes and quarry blasts. Despite urban noise, the network has successfully detected and located numerous small induced earthquakes, with more than 1500 events since 2023 (with a maximum magnitude of 2.4 Mw), significantly surpassing the standard procedure of BCSF-Renass.

## AS25-1166

# Machine Learning- Based Workflow for Earthquake Monitoring in Madagascar

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Enhancing earthquake monitoring is vital to further understanding the tectonic movements and evaluating earthquake risks in a given area. This study aims to develop a near-real-time earthquake monitoring system using machine learning techniques. Our approach consists of five steps: (1) improving phase picking with PhaseNet, (2) associating phases to create events using PhasePApy and the Rapid Earthquake Association and Location (REAL), (3) refining earthquake locations with Hypoinverse, (4) classifying events using a convolutional neural network (CNN), and (5) developing a smartphone application for rapid notification in the event of earthquakes. We tested the new system using earthquake data recorded in Madagascar. Our findings indicate that the new system detected 78% of known events and identified new events, primarily small ones that are challenging for analysts to detect.

As a result, the new system leads to lower magnitude completeness. Most of the missed events were located outside of the seismic network, suggesting that, for a sparse seismic network, the traditional approach and the new automated system are complementary. Additionally, we have enhanced event classification through CNN, a deep-learning method that distinguishes between natural and anthropogenic events. Our findings demonstrate that this method is effective in differentiating between earthquakes and quarry/mining blasts, as well as in identifying quarry/mining sites not included in the training dataset. Lastly, the newly developed application, named SeismicBox2, effectively delivers seismic notifications to smartphones. The new system will eventually be tested in the East African Rift area, where the seismic network is more dense.

## AS25-1171

# Evaluating earthquake location accuracy in simple and complex velocity models using Markov chain Monte Carlo sampling

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Accurate earthquake locations are essential for precise seismic catalogues and unbiased geophysical research, but its accuracy is strongly limited by assumptions on the velocity model used for event location. It is known that a poorly defined 1D model could limit the location accuracy with respect to customized 3D models. Nevertheless, a quantitative assessment of such loss in accuracy is still missing. We conducted an exhaustive comparison between locations obtained using two different elastic models: (1) a homogeneous half-space model and (2) a 3D elastic model specifically developed for the study area, where a dense seismic network is operated. We made use of a Markov chain Monte Carlo algorithm, which furnishes an estimate of the location errors, to compare and evaluate the quality of the retrieved locations obtained with the two elastic models. We analysed different events located in different positions of the study area, to test the performances of both models regarding different geographical positions within the seismic network. Our results confirm previous qualitative findings about earthquake location inverse problem, e.g. that the 3D model better constraints the hypocentral depth, with decreased uncertainties with respect to the homogeneous model. Our study goes a step forward and allow to quantify such improvement in earthquake location. We estimate a reduction of the standard deviations in depth from about one-third up to 90% using a 3D model. These findings indicate that investing in regionally customized 3D models is a more effective strategy for achieving accurate earthquake locations than merely expanding the seismic network.

## AS25-1217

# Magnitudes for local and regional Seismicity in SeisComP — precise and customized

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SeisComP enables precise and reliable automatic amplitude measurement and seismic magnitude estimation, supporting both standard procedures and custom real-time processing. By utilizing data-driven configuration, it produces seismic event catalogs with consistent and unbiased local magnitude estimates, which are essential for accurate interpretation. In contrast, magnitudes computed with default settings can exhibit artifacts, such as overestimation for small events or regional biases. The latest version of SeisComP has optimized the measurement of ML-type amplitudes and the computation of local magnitudes, catering to a wide range of applications and geographical regions defined by seismological research. Key features, including highly configurable waveform windowing, signal quality control, and precise amplitude measurement, ensure unbiased results. Magnitudes are then computed from measured amplitudes using custom parametric or non-parametric calibration functions, tailored to specific distance and depth ranges. The introduction of MLc, a customizable local magnitude, provides exceptional flexibility. Additionally, new methods for regionalization and magnitude aliasing enhance the system's adaptability by incorporating region-specific definitions and aliases, integrating amplitudes with various magnitude types. Our study introduces and demonstrates these advancements in SeisComP and their practical implications.

## AS25-1228

# A new Multi-Method Approach in SeisComP for Monitoring Seismicity in the Tjörnes Fracture Zone, North Iceland

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The Tjörnes Fracture Zone is the largest and most active transform zone in North Iceland comprising the largest strike-slip fault in Iceland, the Husavik-Flatey Fault. Intense seismic sequences occur regularly, sometimes with ~1000 M2–5 earthquakes per month. Being largely offshore, fast automatic event detection and hypocenter location pose a challenge. In 2020–2021, a new strong-motion network was installed in the surrounding area of Husavik including an urban seismic array of seven Raspberry Shake 4D units. For this study we analyzed the performance of the network and the array investigating the seismicity between September and December 2022 and comparing it against the official catalog by IMO. We apply multiple approaches in SeisComP applying combining stacking and deep learning (autothor), array processing (autolambda) and the classic STALTA detection followed by AIC refinement (scautopick). All 3 modules detect phases feeding their picks into scanloc, the cluster search-based location module for SeisComP. Arrival time, backazimuth and slowness information are jointly used for event localization. Although applied here offline, all involved modules support real-time processing. Our comparison shows that the applied methods significantly outperform current automatic event determination. 3D plots and earthquake heatmaps visualize that the seismicity follows active faults, with minimal false positives generated. Our methodology thus enhances detection capabilities and improves the accuracy of earthquake locations for the Husavik region.

## AS25-1236

# Dynamic analysis of the June and December 2023 seismic sequences in the Gulf of Aden

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In June and December 2023 two seismic sequences occurred in the central zone of the Gulf of Aden (46’50 E – 48’30 E). The Gulf of Aden has an ocean ridge that is a part of the triple junction with Afar and Red Sea rifts. Among those, The Gulf of Aden is the rift arm presenting the most swarm activity.

Both 2023 swarms are straddling on oceanic spreading ridge segments and adjacent transform faults at the end of the ridge segments. This coupled with the large error on the earthquake locations means that it is not clear whether the swarms were due to magmatic processes on the ridge or tectonic processes on the transform faults. For June and December respectively, 38 and 50 earthquakes were detected respectively, with magnitudes ranging from 4 to 5.8.

Here we interpret the origin of the activity and the chronology of the sequences with signals from permanent seismic stations in Djibouti and Seychelles. We locate the seismic sequence by using distance-geometry-based method (HADES) that require only two seismic stations and specifically designed for off-network seismicity. In addition, we conduct waveform-cross correlation in order to better understand the temporal evolution of the swarms. Specifically, we interpret the change in waveform similarity through time in light of both our earthquake relocations and available moment tensors from the GCMT. We are questioning the space-time evolution of the seismicity, and the role of the dike intrusion in the segment activity and transform fault activation.

## AS25-1251

# Template matching for identification of hydro-acoustic signals to monitor underwater eruptions

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Volcanic eruptions predominantly occur underwater, but the study of these eruptions remains a significant challenge due to limited site accessibility and the lack of continuous high-resolution data. Consequently, the temporal processes driving the construction of submarine volcanic edifices remain poorly understood. From 2018 to early 2021, one of the largest recorded submarine eruptions occurred 50 km east of Mayotte, in the Mozambique Channel, leading to the birth of the Fani Maoré volcano.

The Fani Maoré eruption presents a rare opportunity to study submarine volcanic dynamics. Form early 2019 to the end of the eruption, ocean bottom seismometers (OBS) deployed offshore Mayotte have recorded hydro-acoustic signals generated by the eruptive activity. These signals provide unprecedented temporal precision for tracking volcanic activity and lava flow emplacement.

In this work, we employ template matching to detect impulsive hydro-acoustic signals from the hydrophone component of the OBS dataset. Templates are constructed by clustering manually picked events. We then associate the detected signals with their sources to reconstruct the spatio-temporal variability of eruptive activity. This approach enables us to highlight key phases of the eruption, offering new insights into submarine volcanic processes and paving the way for continuous, high-resolution monitoring of underwater eruptions.

## AS25-1269

# Fractal properties of some seismic sequences following important earthquakes in northern Morocco and Alboran Sea

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An important earthquake of magnitude Mw=6.3 struck in Alboran Sea, North of Morocco, on January 25, 2016. The epicenter was located about 50 km NNE of Al Hoceima, the most seismically active region of Morocco. The hypocenter was estimated around 10 km.

The aftershocks sequence following the Alboran main shock (552 events with M>3 during 15 days) has been investigated by non-linear tools. The inter-event time between successive aftershocks is analyzed to study their temporal structure and clustering properties.

From the Gutenberg-Richter law, the *b* value is found to be around 0.69. The Omori law exponent is high (1.95) for a period of 7 days. Korçak fractal exponent is around 1.75. The autocorrelation function shows a high degree of correlation and persistence memory only during the first week, after that another temporal structure organization began. This latest observation is not in agreement with Hurst analysis which indicated a continuous and nearly uniform aftershock activity with high persistence behavior (H~0.81).

Al Hoceima region was struck also by an important earthquake (Mw=6.1) on February 24, 2004; inducing a devastating damage and 629 victims. The time dynamics of the sequence following the main event (during 15 days) has been investigated also by fractal tools.

The study and the comparison of the inter-event times of Alboran and Al Hoceima seismic sequences have been made; and the results showed some similarities but also and above all important differences related to their scaling properties and continuity even though similar mean shock magnitudes, focal mechanisms and geodynamic context.

## AS25-1370

# Rapid and Delayed Activation of Off-Fault Clusters post L'Aquila 2009 and Central Italy 2016 Sequences

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The activation of faults by nearby earthquakes can occur by different mechanisms, each influenced by the state of stress and its sudden fluctuations, fault geometry, frictional properties and external forces. The basic modes of fault activation include dynamic triggering, earthquake interaction, changes in pore pressure, thermal effects and aseismic transients. These processes interact almost simultaneously, and it is often difficult to understand the evolution of seismicity patterns and the primary process that causes significant changes in crustal fault systems. Knowledge of fault geometries, their segmentation and other structural heterogeneities can hinder further investigation of productive earthquake sequences. Here, we analyze the behavior of the Campotosto seismic area, and its activation after the main earthquakes in central Italy. The area was affected by three M>5 earthquakes immediately after the 2009, Mw6.3 L'Aquila earthquake, and four M>5 events two and a half months after the 2016, Mw6.5 Norcia main earthquake. We use high-resolution earthquake catalogs to identify clusters that stand out from the background seismicity, and we propose possible main drivers that may have influenced the frictional resistance of the fault and the influence of fluids in reducing the effective normal stress, thereby facilitating fault slip.

## AS25-1404

# Detecting low-magnitude events in a noisy environment: an AI-assisted catalog for the Lower-Rhein Embayment region, Germany

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The Lower Rhine Embayment (LRE) is one of Germany's most seismically active regions, where historical records provide evidence for a total of nine Ms > 5 earthquakes in the region near Aachen. In the context of the SIEGFRIED project, creating a high-resolution earthquake catalog to quantify background seismicity and study the active structures in the region is necessary to ensure safe and economical geothermal energy production. Nevertheless, the comparatively high average noise level above 1 Hz in the LRE (primarily of anthropogenic origin) hinders classical automated earthquake detection routines, particularly for low-magnitude events (M<0.5). In this work, we implement an AI-based workflow to monitor seismicity in the LRE, which includes signal enhancement using a decoder-autoencoder denoiser (Heuel et al., 2022) and phase picking with PhaseNet (Zhu et al., 2018). After fine-tuning, we detect 952 seismic events that occurred between January 2021 and January 2023, of which 281 were reported in a manually detected reference catalog (BNS), 325 correspond to quarry blasts, and 302 are newly reported events. Our workflow doubled the number of earthquakes reported by BNS, missed 32 events, and had two false detections. Additionally, we combine DAS recordings with template matching on continuous seismic waveforms to infer a new family of anthropogenic events related to the metal industry in the area. We will present the extended earthquake catalog from 2019 to 2025 produced with the newly developed workflow, and, given the variety of sources, discuss the use of automatic signal discriminator to avoid event misinterpretation.

## AS25-1408

# Unveiling the aftershock activity following the 2010 Mw 8.8 Maule earthquake

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Recent advances in earthquake detection and location using modern algorithms have significantly improved earthquake catalog resolution and completeness. However, detecting small-magnitude events remains challenging, particularly shortly after large earthquakes or during periods of reduced network coverage. These gaps introduce biases that can affect seismicity rate estimates, b-value calculations (describing the ratio of small to large earthquakes), and magnitude of completeness (Mc), leading to potential misinterpretations of seismic sequences.

Using an AI-based detection algorithm and an automated processing routine, we constructed a deep-learning earthquake catalog with more than 375,000 events recorded in the 10 months following the 2010 Mw 8.8 Maule earthquake, from a spatiotemporally sparse seismic network. This study analyzes how variations in network coverage could impact observed seismicity rates and whether changes in aftershock activity reflect real fluctuations or detection biases. To address this, we apply a probabilistic correction model to account for time-dependent Mc variations, aiming to refine aftershock decay rate estimates and frequency-magnitude distributions. Additionally, we compare classical b-value estimation with the b-more-incomplete method, which is proposed to mitigate catalog incompleteness.

Through this approach, we aim to assess the necessity of magnitude of completeness corrections in large-scale seismic datasets and explore their potential to provide a more reliable framework for aftershock sequence analysis and its potential role in seismic hazard assessment.

## AS25-1413

# Real Time W-phase Wavelet Domain Finite Fault Inversion

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In centroid moment tensor inversion methodologies, the W-phase has proven to be a reliable and robust method for large earthquake characterization, providing key macro seismic parameters that allow for a prompt evaluation of the tsunamigenic potential of large earthquakes. Moreover in regional networks its implementation has been extended to lower magnitudes, examples of this are Chile, United States, Japan, Mexico among others. Here we extend the capabilities of this long period wave to Finite Fault Models taking advantage of its fast arrival and long period that does not get affected by the upper crust. Instead of the traditional time domain deconvolution we extract the W-phase the wavelet domain using carefully the coefficients that more accurately can model the W-phase. Here we test the method retrospectively for the following events: The 2010 Mw 8.8 Maule Earthquake 2, The 2010 Mw 7.8 Mentawai Tsunami Earthquake, The 2011 Mw 9.1 Tohoku Megathrust Earthquake, The 2015 Mw 8.3 Illapel Earthquake and The 2010 Mw 7.2 El Mayor Earthquake and The 2023 Mw 7.8 Turkey Earthquake. We also incorporate a real time implementation and we benefit from the extraction of the W-phase in continuous GPS data, which makes it possible to use from 5° obtaining a first finite fault model 6 minutes after origin time, including local and regional stations that with the traditional teleseismic finite fault modeling methods are not possible to include.

## AS25-1417

# A note on the errors in fault slip inversion

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In inversion analyses, we have to assume statistical characteristics of errors. If this assumption is inappropriate, severely biased solutions can be obtained. For example, when errors are correlated between data, we must take covariance components into account (e.g., Fukahata & Wright, 2008; Yagi & Fukahata, 2008, 2011). Then, how should we assume the statistical characteristics of errors?

In order to address this problem, we have to consider the origin of errors. In general, errors originate from various sources, which can change for individual problems. In other words, the essence of error treatment lies in a specific problem, not in general theory. In this paper, we take fault-slip inversion as an example.

In fault-slip inversion, the observation equation can be written in a vector form as, d=Hm+e, where d is a data vector to represent observed displacements on the Earth's surface, m is a model parameter vector to represent the slip distribution on a fault plane, H is a coefficient matrix that includes the Green's function to relate the displacement on the Earth's surface with a slip on the fault plane, and e is an error vector. Here, the problem of this paper is to clarify the components of the error e. In my view, the components of the error in fault-slip inversion can be classified into the following four categories: (1) errors associated with the Green's function, (2) discretization error, (3) errors associated with observation, and (4) errors of observation station. In IASPEI meeting, I will explain the detail.

## AS25-1427

# Real-time Production and Analysis of High-Precision, Deep-Magnitude Earthquake Catalogs

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The growth in seismic data over the past decades has sparked the development of new algorithms for efficiently computing earthquake catalogs at unprecedented completeness, resolution and scales. Sometimes, these catalogs include millions of earthquakes with parameters constrained by billions of measurements, and can span decades of observations at local to plate tectonic scales. The increase in availability of streaming seismic waveforms offers the opportunity to implement and test these methods for real-time monitoring of earthquake activity and changes in source or fault properties. Here, we demonstrate the performance of several methods: supervised machine learning (ML) and waveform cross-correlation for event detection and phase arrival and delay time measurement; unsupervised ML for event characterization and discrimination; grid search and double-difference methods for absolute and precise, relative hypocenter location, respectively. We tailor these tools to work in modular workflows that efficiently handle massive amounts of data, both for retro-active processing to build high-resolution catalogs and for real-time monitoring as new events occur. We present operational monitoring results for the cabled OBS array at Axial seamount with focus on real-time detection and analysis of precursory signals leading up to the next eruption, the NCSN seismic network in northern California with focus on detection and monitoring of repeating earthquakes, and the LCSN network in the northeastern U.S. with focus on computing a deep-magnitude catalog in a low strain rate region. Ongoing efforts within the SCOPED project focus on implementing these modules on a community accessible, hybrid cloud-HPC platform.

## AS25-1443

# A Deep Learning-Based Smart Seismic Activity Prediction for the Southern California Region

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Predicting the earthquake magnitude has remained a complex challenge for researchers over the decades. This project focuses on developing advanced machine learning and deep learning models to accurately predict seismic event magnitude. In this study, the earthquake magnitude are classified using deep neural networks, logistic regression, SVM, and random forest algorithms. Since, earthquake is highly heterogeneous in nature, data inequality and extracting the relevant features from the data pose a difficulty in performing prediction, so, in order to overcome such difficulty, the Synthetic Minority Over-sampling Technique (SMOTE) is applied to overcome the inequality and for increasing the data quality. Feature engineering is performed on the dataset by applying seismic principles such as the Gutenberg-Richter law, and likelihood and least squares has been calculated. The models are trained on preprocessed data of california, and their performance is assessed using evaluation metrics like precision, recall, and the F1 score. Various machine learning and Deep learning techniques, including Artificial Neural Networks (ANNs), Random Forest, and Support Vector Machines (SVMs), have been employed in seismic activity prediction. From the retrospective analysis, the results indicate that the accuracy and reliability of this approach in earthquake magnitude prediction are considerably higher compared to conventional methods. This project effectively demonstrates how machine learning and deep learning techniques can significantly improve earthquake prediction in the confined study region.

## S05 Frontiers in Fiber-Optics Sensing in Seismology

### AS25-0098

# Fiber Sensing with Internet Cables: A long-term observation of various environmental processes using laser interferometry

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Many oceanographic and offshore geological processes are currently poorly understood, particularly their triggers and re-occurrence rate, due to difficulties associated with direct monitoring. The main challenges in this regard are the vast size of the ocean and costs related to instrument deployments. In this study we aimed to understand the effectiveness of fiber sensing using laser interferometry to detect various offshore processes. This sensing technique allows usage of the existing telecommunication network while generating manageable data volumes, which enabled us to acquire data for over one year from the central Mediterranean Sea. In detail, we used laser interferometry on a 260-km long telecommunication fiber located between Sicily and Malta. The acquired fiber records show a wide range of signals originating offshore, which we successfully correlated to different environmental processes by using complementary data sets. Our experiment shows that the fiber in the telecommunication cable reliably detects the signature of earthquakes, oceanographic microseisms primarily from wind-wave interaction, as well as tides, internal gravity waves and vortices. We further observed a signal of infrequent occurrence over the span of several days and with stronger cable oscillations at higher frequencies (1–10 Hz) compared to other signals, which we tentatively associate with submarine sediment flows, but more tests are needed to determine its origin. This study demonstrates that laser interferometry is a promising monitoring tool and in addition to data from other sensor networks has the potential to significantly improve our understanding about the occurrence and effects of various oceanographic and offshore geological processes.

## AS25-0207

# From Points to Lines: A Hybrid Approach to Earthquake Localization with integrated fiber sensing data

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Traditional earthquake localization methods rely on classical seismic sensors, which we may refer to as point sensors. These sensors provide precise, discrete measurements at specific locations. However, emerging technologies allow for the use of line sensors, such as fiber optic cables, which integrate measurements along their length. Examples of such techniques include laser interferometry and State of Polarization (SOP) measurements. In this case, the picking of the seismic phase is also precise but is not anymore associated with a point in space. From a technical standpoint, in two-dimensional space, a minimum of three line sensors is required to locate an event, similar to the principle applied to point sensors. The most effective approach to achieving this is through the use of time maps across the entire medium. Once sensors—whether point or line—are translated into time maps, their merging becomes independent of the sensor type. This approach enables the integration of both sensor types for earthquake localization. To test these assumptions, we have employed the Fiber Sensing code, which fundamentally relies on time maps. We will present various synthetic tests to validate our methodology and an application to real data, incorporating measurements from ultra-stable laser interferometry alongside traditional phase arrival data from point seismic stations. The results highlight the feasibility and advantages of incorporating line sensors into earthquake localization frameworks, paving the way for more robust and versatile seismic monitoring systems.

## AS25-0232

# Revealing lakebed sedimentary history in Yigong Lake, Tibetan Plateau using distributed acoustic sensing

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Yigong Lake, formed by a landslide in 1900, remained stable until a second landslide in 2000 breached the dam, causing significant economic losses and devastating downstream disasters. Located in the active convergence zone of Tibetan Plateau, the lake's shallow structure is crucial for assessing geohazards and advancing research on sedimentation and geodynamics. This study uses Distributed Acoustic Sensing (DAS) technique to image the lakebed sedimentary layers. By deploying fiber-optic cable, including 725 meters buried beneath the lakebed, we identified three layers: a uniform upper layer of unconsolidated sediments, a laterally thickening middle layer with variable compaction and deposition from multiple processes, and a deepest layer with relatively low velocities, compacted sediments reaching depths of 110 meters but not extending to bedrock. Forward modeling confirmed the accuracy of our results, providing valuable insights into landslide-dammed lake dynamics and hazard mitigation, while also demonstrating portable DAS's reliability in remote, complex environments.

## AS25-0238

# Distributed acoustic sensing seismic observations using fibers on seafloor cable observation systems installed in Japan

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A seismic observation using Distributed Acoustic Sensing (DAS) provides spatially high-density data along a fiber for a long distance. DAS measurement using seafloor cables can increase the number of seismic stations in marine areas. A seafloor seismic and tsunami observation system using an optical fiber cable off Sanriku was deployed in 1996. We have performed temporary DAS measurements since February 2019 using spare fibers of the Sanriku system. In 2010, the ERI also installed a seafloor cable observation system in the Japan Sea. From April 2023, temporary DAS measurements were sporadically performed using a fiber with a length of about 22 km. Especially, the aftershock observation of the 2024 Noto-Hanto earthquake was conducted from February to May 2024. As a result of these observations, many earthquakes including micro-earthquakes and teleseismic events were observed. The noise levels of the DAS measurement were comparable to those of conventional servo-type accelerometers. The Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net) is being constructed in the western Nankai trough area. A half of N-net was deployed in early 2024 and a pilot DAS observation was performed from August to October 2024. During the pilot DAS observation, a large earthquake with a magnitude of 7.1 and the following aftershocks near the cable system were recorded. Using the records of large events, performance of DAS measurement under a large deformation was recognized. Experience of observations using DAS technology on actual seafloor cables around Japan reveals capability of DAS measurement as a seismic observation.

## AS25-0308

# Investigating Stromboli volcano using Distributed Acoustic Sensing

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Distributed acoustic sensing (DAS) provides high-resolution recording of strain rates in both space and time, offering a powerful tool for monitoring volcanic activity. We deployed a 3 km optical cable on Stromboli volcano and measured strain rate over several months during 3 years. To validate these recordings, we compared them with colocated nodal seismometers. By converting node measurements to strain rate, we observe a perfect phase match between DAS and node waveforms for both tremor and volcanic explosion. However, DAS amplitudes are about 3 times smaller than those of node records, which we explain as due to the inefficient ground-to-fiber strain transfer in the loose cable. Using seismic interferometry, we image the shallow structure beneath the optical fiber. Time segments from DAS channel pairs are cross-correlated using phase correlation and stacked using the time-frequency phase weighted stack method to obtain the empirical Green functions. Both phase and group velocities are inverted to determine the shallow S-velocity structure. Structure variations along the optical cable correlate with changes in topography rugosity and can be related to different ash and lava deposits. Additionally, we investigate long period DAS data which allows monitoring the volcano's principal axis of deformation. Finally, we demonstrate that DAS data can track pyroclastic flows showcasing its potential for comprehensive volcanic surveillance.

## AS25-0357

# Full-Waveform Inversion for Source and Structure of DAS Data on a subglacial Volcano: Grímsvötn, Iceland

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We present the results of an experiment with Distributed Acoustic Sensing (DAS) on the Grímsvötn volcano in Iceland, and the potential for Full-Waveform Inversion (FWI) with DAS for source properties and Earth structure.

Grímsvötn is one of Iceland's most active volcanoes and is covered by the Vatnajökull ice cap. A 12 km long fibre-optic cable followed the caldera rim and ended near the central point of the caldera on top of the subglacial lake, where we acquired data for one month in May 2021.

Here, we build upon previous results of microseismicity that has been located with first-arrival times and a homogeneous half-space assumption. We select ~10 high-quality events that originate near surface expressions of the caldera fault. Combined with a starting model that includes the complex topography and ice sheet, we iteratively optimise the moment tensor components and refine the source locations in the frequency range of 1.5–3 Hz with FWI. To avoid local minima in this highly non-convex inverse problem, we combine different strategies such as simulating a range of random moment tensors, source-time-function inversion and sequentially updating moment tensor components and source location. The inverted sources are used in a proof-of-concept study to invert for structure, showing small-scale velocity anomalies related to the geothermal activity of the subglacial volcano.

Local-scale source and structure FWI inversions are challenging, and we hope that our findings will contribute to the high-resolution modelling of volcano-tectonic microseismicity and velocity anomalies, increasing our understanding of subglacial volcanoes and their geothermal dynamics.

## AS25-0399

# Shallow subsurface imaging along a total of 12 km section of Route 47, Japan, using surface waves and DAS

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We used distributed acoustic sensing (DAS) data recorded by a 31 km long fiber-optic cable along National Route 47 in Miyagi Prefecture, Japan, to investigate shallow subsurface structures.

Surface wave dispersion curves were estimated using the phase-shift method and automatically picked up to the first higher mode of the Rayleigh waves. Shear wave velocity profiles down to 100 m depth were then obtained by modeling numerous layered structures.

Our results reveal significant spatial variations, including soft sediments with shear velocity of less than 300 m/s in the riverbed and an underlying high-velocity layer (~600 m/s) beneath the lower reaches of the Eai River, which was previously unrecognized. To evaluate our estimates, we compared them with the average shear wave velocity above 30 meters depth (AVS30). Our AVS30 values show good agreement with the dataset published by the National Research Institute for Earth Science and Disaster Resilience (NIED), which provides nationwide AVS30 estimates based on borehole measurements and spatial interpolation, while also resolving finer-scale subsurface features.

Clear dispersion spectra were obtained over a large portion of the survey line, which spans diverse terrains such as an alluvial plain, mountain foothills, and small-scale river terraces. This enabled imaging of both large-scale geological structures and localized subsurface features over a 12 km section—achieving a spatial coverage that only a few on-land studies have reported. These findings highlight DAS's potential for high-resolution and large-scale seismic imaging across diverse geological settings.

## AS25-0436

# Fault Structure Characterization Using DAS and Vibroseis Technology: A Case Study in the Tangshan Seismic Zone

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The Distributed Acoustic Sensing (DAS) system, an emerging vibration monitoring technology in seismology characterized by ultrahigh spatial sampling density, was implemented for seismic signal acquisition along a 7-kilometer segment of pre-installed urban communication optical fibers in the Tangshan region. The deployment utilized Silixa's iDAS equipment configured with a 10-meter gauge length, achieving a spatial sampling interval of 4 meters. The fiber-optic array was strategically positioned across the Tangshan Guye Fault, the causative structure of the 1976 Tangshan earthquake. A 28-ton vibroseis truck executed dense active seismic source deployments at 8-meter intervals along the fiber trajectory, generating controlled sweep signals(5–110 Hz frequency range, 10-second durations). Precise documentation of source excitation timing and spatial coordinates was maintained throughout the operation. Data processing commenced with extraction of seismic waveforms through cross-correlation analysis between the continuously recorded DAS signals and the transmitted sweep signatures. Subsequent analytical procedures incorporated first-arrival travel-time tomography for velocity structure inversion and reflection wave stacking for subsurface imaging. The integrated approach successfully delineated fault architecture (including spatial positioning, dip characteristics, and rupture dimensions) and identified low-velocity zones at depths reaching 200 meters, with derived parameters exhibiting remarkable alignment with established geological records. This experimental investigation substantiates that the synergistic application of urban telecommunication infrastructure repurposed for DAS-based seismic monitoring, coupled with vibroseis source excitation techniques, provides an effective methodology for high-resolution near-surface geological profiling. The operational framework demonstrates substantial cost-reduction potential for shallow seismic exploration targeting active faults in urbanized areas, while maintaining requisite geophysical diagnostic capabilities.

## AS25-0463

# SAFAtor: A Major Helmholtz Infrastructure Project for Coastal and Ocean Monitoring with SMART Cables, Fibre-Optic Sensing, and Advanced Data Services

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Launched in March 2025 as a €30 million initiative by the German Helmholtz Association, the SAFAtor project (SMART cables And Fibre-optic sensing Amphibious demonstrator) aims to address critical observational gaps across the continental shelf, slope, and deep ocean using cutting-edge cable technologies.

SAFAtor integrates Distributed Acoustic Sensing (DAS) into three Plate Boundary Observatories located in Northern Chile, the Marmara Sea, and Mount Etna, significantly enhancing monitoring capabilities for tectonic and volcanic activity (as highlighted in the presentation by Krawczyk et al.). Additionally, SAFAtor builds on insights gained from the European SUBMERSE project, set to conclude in 2026, and will establish a submarine telecommunication cable demonstrator equipped with advanced sensor technology to measure temperature, absolute pressure, and ground acceleration on the seafloor.

To support these goals, SAFAtor develops an open, interoperable FAIR data infrastructure designed to process and distribute DAS and cable data, integrating with German (NFDI4Earth) and European (EPOS, EMSO, Copernicus Marine Services) data services. Developed alongside the EU GeoInquire project, these innovative data management strategies will ensure machine learning readiness through adherence to FAIR principles and the integration of key performance indicators and ML analysis tools. The project adopts an end-to-end approach, ensuring seamless data flow from sensor deployment to end-user applications.

Addressing key technical challenges, SAFAtor will assess the capabilities of new DAS devices in recording strong-motion events for seismic hazard assessment, develop strategies to balance privacy and security with open science for reproducibility, and foster ongoing discussions and working groups to adapt to rapidly evolving technologies, costs, and policies.

## AS25-0480

# Controlled lossy compression of distributed acoustic sensing data for large-scale monitoring

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Efficient compression of distributed acoustic sensing (DAS) data is essential for real-time monitoring and long-term storage in large-scale seismic and environmental studies. While lossy compression methods significantly reduce data size, it is crucial to control the introduced distortion to maintain scientific validity and preserve the integrity of physical interpretations.

We introduce a customizable compression framework specifically designed for DAS data. Our approach applies a 2D wavelet transform to time-distance data, decomposing signals into frequency and spatial components. We also use linear predictive coding in both dimensions to exploit correlations, resulting in a more compact representation of the data. The reduced data is then quantized with adjustable precision, followed by entropy coding to achieve efficient compression while maintaining scientific fidelity.

Recognizing the diverse requirements of varied DAS monitoring scenarios, our method offers tunable distortion levels tailored to specific scientific goals. These include preserving frequency content, phase coherence, amplitude accuracy, inter-channel coherence, and long-distance spatial correlations. By explicitly defining distortion measures for each frequency band and analyzing phase shifts, we quantify the impact of compression on data fidelity. Additionally, we assess how compression alters ambient noise characteristics, distinguishing between beneficial noise reduction and unintended signal distortion.

## AS25-0492

# Earthquake monitoring in the Azores with distributed acoustic sensing

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The MODAS project "Monitoring the Ocean with DAS" used an HDAS system from Alcalá University to monitor the subsea telecommunications cable owned by Fibroglobal[8], connecting the islands of Faial and Flores -. The HDAS employs phase-sensitive optical time-domain reflectometry (phi-OTDR) to measure strain variations along 50 kilometers of cable, with a spatial resolution of 10 meters at a sampling rate of 50 Hz. The HDAS recorded between 14/12/2023 and 10/11/2024.

To obtain pseudo-transfer functions between strain-rate and ground motion, two broadband Ocean Bottom Seismometers with hydrophones were deployed near the cable from July to December 2024 when land stations on Faial and Pico recorded 245 local and regional earthquakes (magnitudes -0.6 to 5.0). HDAS data shows an $1/f$ increase in background noise level below 1 Hz, hindering the detection of low-frequency signal, such as teleseismic earthquakes.

Preliminary analysis shows that P-waves are detected by HDAS only in the strongest ground motion events, whereas S-waves are recorded more consistently, with quality depending on magnitude and distance.

HDAS waveforms show a significant loss of coherency between neighboring channels while interrogator noise remains highly coherent. This suggests an averaging filter with subtraction could enhance signals. Despite uncertainties in HDAS time stamping (~ a few seconds), the large number of channels proves valuable for offshore event localization.

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## AS25-0521

# Near-coast fibre-optic sensing within the Helmholtz infrastructure project SAFAtor

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The SAFAtor project (SMART cables And Fibre-optic sensing Amphibious demonstrator) has been kicked-off as a €30 million infrastructure initiative by the German Helmholtz Association in March 2025, to investigate critical observational gaps from the continental landmass to the shelf and slope (Workpackage 1; focus of this presentation), and in the deep ocean using novel cable technologies (Workpackage 2). The full concept, including intended data services (Workpackage 3), is highlighted in the presentation by Cotton et al. (this conference).

At Mount Etna/Italy, in the Marmara Sea/Turkey, and in Northern Chile, we will integrate Distributed Acoustic Sensing (DAS) into existing Plate Boundary Observatories to address key questions on volcanic processes, fault dynamics, and preparatory phases of earthquakes. Thereby, we want to significantly enhance monitoring capabilities observing tectonic, volcanic, and fluid-driven activities. Further, we tackle technical challenges like amphibious monitoring and recording of strong-motion events for seismic hazard assessment. Using both well proven and also new DAS devices, we will complement this rapidly evolving field also in urban areas. This will allow us to explore near-surface structures and material properties, as well as hydrological processes in connection with hazardous events.

In our presentation we will address the specific targets of the different tectonic regimes investigated. We will discuss the experimental setups that we have started implementing in the light of first data gained, helping to optimize hazard research using distributed dynamic strain sensing techniques.

## AS25-0615

# Secondary Microseism Source and Propagation Analysis Using Full Waveform Modelling and DAS Observations Offshore Catania, Sicily

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Low-frequency microseism signals generated by ocean wave interactions propagate large distances, preserving information about ocean wave states and source locations. Nonetheless, they can also be influenced by seismic wave propagation effects.

This study combines Distributed Acoustic Sensing (DAS) in an optical-fibre cable with full-waveform modelling to analyse a singular secondary-microseism event and associated path effects between its source and receivers. The DAS data was collected over five days along a 29 km optical-fibre section of the INFN-LNS subsea infrastructure offshore Catania, as part of the FOCUS-ERC project.

DAS data analysis identifies a prominent energy in the secondary-microseism frequency band, for a prolonged duration. Leveraging a 20 km straight-line section of the cable, Frequency-Wavenumber (FK) analysis over successive time windows reveals equal energy propagation in both seaward and landward directions suggesting a microseism source south of the cable. Wind data and ocean wave models confirm a source region south of Sicily linked to local weather changes. Although the ocean wave model aligns with the FK observations, FK plots show a contradictory dominant seaward propagation as the source moves eastwards. Cross-correlation analysis of microseism wavefields over different cable sections implies this discrepancy emerges from the cable's end section.

Forward seismo-acoustic simulations incorporating regional bathymetry, validates DAS observations by demonstrating that the shift to dominant seaward propagation near the cable's end results from the redirection of the microseism wavefield by the continental shelf. These results highlight the impact of bathymetry and source position on microseism propagation and the potential of DAS for high-resolution seafloor seismic monitoring.

## AS25-0654

# A new Distributed Acoustic Sensing (DAS) metadata standard proposed as an FDSN standard

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Distributed Acoustic Sensing (DAS) is a transformative technology and its applications in geosciences and engineering are numerous and growing. To move this frontier technology forward, it is important to implement a metadata standard specifically for DAS to facilitate the comparison and integration of DAS measurements across deployments and make the data reusable following Findable, Accessible, Interoperable, and Reusable (FAIR) data principles. Long-standing metadata standards for seismic data such as the Standard for the Exchange of Earthquake Data (SEED) do not adapt well for DAS due to fundamental differences in sensor and data acquisition parameters. With community input gathered from conferences, online discussions, and a whitepaper between 2020 and 2023, the DAS-RCN Data Management group proposed a DAS metadata standard (Lai et al., 2024). The metadata standard fully describes the five key components of a DAS experiment: (1) interrogator; (2) data acquisition; (3) channels; (4) cable; and (5) fiber. The schema is hierarchical based, with a parent "overview" metadata block describing the experiment, and two main child branches describing the instrument (i.e., interrogator, photonics setup, and acquisition parameters) and the sensor locations (i.e., cable installation and fiber properties). The metadata standard can be applied to common scenarios such as dark fiber and borehole cable, and complex settings with multiple interrogators to multiple cables. The metadata standard is being proposed as an FDSN standard and moved to the FDSN GitHub organization to enable community collaboration and development, as the DAS technology and application continue to evolve.

## AS25-0678

# South Island Seismology at the Speed of Light Experiment (SISSLE) — characterizing the Alpine Fault at Haast, New Zealand

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We introduce initial results from a DAS array deployed in two phases for nearly 5 months between late-February and mid-May 2023 and again in October–November 2023 on the South Island of New Zealand. The South Island Seismology at the Speed of Light Experiment (SISSLE) utilizes two lengths of telecommunication fiber: one running roughly parallel to the Alpine Fault (~18 km) and the Tasman Sea and the second that runs perpendicular to and crosses the Alpine Fault (~30 km). The Alpine Fault marks the boundary between the Australian and Pacific plates. Haast lies near a geometrically and paleoseismically distinctive segment boundary where large (~M8) earthquakes appear to preferentially nucleate and terminate on ~300-year timescales.

With the high temporal (1 kHz) and spatial (4 m) resolution, data from an iDAS unit have demonstrated improvements in the detection of weak seismic sources, including low-magnitude earthquakes diagnostic of fault activity, and distinct waveform complexity originating within the fault zone. Given the large volume and complex nature of the data, machine-learning methods have been developed to enhance signal detection. The dense spacing across the Alpine Fault has allowed for high-resolution imaging of the fault zone including the near-surface fault geometry and structure using correlation, tomography and waveform modelling techniques. Our analyses to date have focused on detection and characterization of thousands of local and regional events and are using these data, in additional to ambient noise, to better image the mapped fault zone and to improve our understanding the structures associated with the fault.

## AS25-0686

# Distributed Acoustic Sensing for Urban High-Resolution Subsurface Imaging: A Case Study in Istanbul

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Istanbul in northwestern Turkey is situated in one of the world's most tectonically active regions and is one of the areas in Europe with highest earthquake hazard. Its large population and critical infrastructure make it highly vulnerable to geohazards, posing risks to human life and economic stability. Understanding the fault structure in the shallow subsurface can provide essential insights for hazard and risk assessment, but logistical constraints and human activity limit the application of traditional geophysical surveys in urban areas. To address these challenges, we explore using Distributed Acoustic Sensing (DAS) deployed on dark fibers to enable efficient subsurface imaging at high spatial and temporal resolution in dense urban areas such as Istanbul.

Since May 2024, a DAS system has been continuously recording passive seismic data along a 17 km-long dark fiber in Istanbul's Kartal district. We aim to apply ambient seismic noise interferometry to extract high-resolution velocity models and detect hidden faults, contributing to hazard assessment. However, dark fiber-based imaging in urban areas presents multiple challenges, including vast data volumes, complex noise environments, and unconventional array geometries. To maximize the potential of DAS, we develop tools that optimize these datasets and evaluate diverse ambient noise sources, including train tremors and microseismic signals, assessing their effectiveness in urban contexts. The variety of frequency content of these sources enables multiscale, multiresolution imaging. These efforts aim to enhance high-resolution subsurface imaging and improve our understanding of seismic hazards, offering a scalable approach for risk assessment in Istanbul and other vulnerable urban areas.

## AS25-0702

# Study of parameter correlations from submarine DAS data analysis and from optical fiber signal propagation models

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Distributed Acoustic Sensing (DAS) is an advanced event detection technology that has matured over decades across industries. Its potential for real-time monitoring of natural hazards along submarine fiber is now widely recognized. Multiple studies aim to establish reliable correlations between detected signals and geophysical parameters.

While data-driven approaches have demonstrated meaningful correlations, high-reliability real-time seismic or tsunami detection also requires advanced modelling. This study examines parameter correlations between submarine DAS data and modelled signal propagation in optical fibres.

Using DAS datasets from the MODAS project in the Azores, we implemented a Python-based preprocessing pipeline to convert received DAS data into a standard seismological format. Data analysis techniques were applied to extract key parameters.

The DAS instrument measures optical phase changes via Rayleigh backscatter (phase-sensitive OTDR), detecting strain variations up to 50 Hz, in every 10 m fibre element, along 50 km. We study optical fibre propagation models, focusing on phase evolution, and employ numerical models to refine parameter correlations.

The correlation of parameters from submarine DAS data analysis with those from modelled optical signal propagation will be discussed. Results can offer insights into data analysis procedures and calibration techniques.

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## AS25-0704

# DeepDAS: An Earthquake Phase Picker for Submarine Distributed Acoustic Sensing Data

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Due to limited deployment, traditional seismology faces greater challenges in oceanic regions compared to inland areas. Submarine Distributed Acoustic Sensing (DAS) systems offer a promising alternative for seismic monitoring in these areas. The EU-INFRATECH-funded SUBMERSE project will enable continuous monitoring of several oceanic telecom cables at landing sites in Portugal, Greece, and Svalbard. However, existing machine learning models trained on land-based DAS data underperform with submarine DAS.

This study introduces a machine learning approach specifically for submarine DAS data to enable automated seismic event detection and identification of P and S waves. Leveraging DeepLab v3, a neural network architecture optimized for semantic segmentation, we developed a specialized model to address the challenges of submarine DAS data. The model was trained and validated on a dataset comprising nearly 92 million manually and semi-automatically labeled seismic records from multiple international submarine sites, providing a robust foundation for accurate seismic detection. We compared the performance of DeepDAS and PhaseNet DAS in identifying seismic P and S waves from submarine DAS data. Our findings indicate that DeepDAS (F1 score: 0.89) significantly outperforms PhaseNet DAS (F1 score: 0.53) on these datasets. This performance gap is expected, as PhaseNet DAS was originally trained on land-based DAS seismic data.

Additionally, we created a comprehensive submarine DAS earthquake dataset with 6,326 manually labeled seismic events (magnitudes -2 to 5, depths 0–200 km) across diverse deployment scenarios. To foster collaboration and reproducibility, we plan to open-source this dataset as a benchmark for submarine DAS research.

## AS25-0725

# Monitoring Earthquake Activity using DAS data from offshore submarine cables in the Ionian and Aegean Seas

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Recently, distributed acoustic sensing (DAS) has become a valuable tool for recording seismic wavefields across broad frequencies, enabling high-density measurements in remote offshore areas. DAS systems offer key advantages for seismic monitoring in regions like Greece, where complex island topology challenges traditional observations. In this work, two fiber optic cables already deployed in the Ionian sea (Preveza/Greece to Crotone/Italy) and Aegean sea (Rhodes island to Kos island) are being tested. In both cases, DAS dense measurements are conducted, sampling an area of approximately 150 km in each case. Apart from the full large dataset exploited by the consortium, decimated channels (~100 in each case) acted as virtual seismic stations offshore are acquired through the SeedLink protocol in NOA operational datacenter for realtime monitoring purposes. For Preveza deployment, the fiber is located at the westernmost part of the Hellenic subduction zone, a region characterized by frequent seismic activity, including strong earthquakes (M > 6) in the Kefalonia Transform Zone. For Rhodes deployment, the fiber traverses multiple fault systems in the easternmost subduction back-arc area that generate moderate to strong seismicity and is passing near the active volcanic center of Nisyros. In this study, we present preliminary observations aimed at assessing datasets quality and evaluating earthquake detectability. Additionally, we explore various approaches to phase picking and signal analysis while attempting to locate in realtime local seismic events recorded during the experiments. Finally, we discuss potential insights into submarine structures of the testing area based on seismic observations.

## AS25-0745

# Facilitating DAS virtual stations streaming to data centres and seismic networks

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Distributed acoustic sensing (DAS) can leverage marine fibre-optic cables to vastly extend the coverage of conventional seismic networks. A subset of the channels from the large DAS arrays can be used to generate virtual stations with acquisition parameters and data rate similar to conventional seismic stations. For example, a 120 km long cable can stream 12 virtual stations with an inter-station spacing of 10 km. DAS data pre-processing using the large aperture and dense spatial sampling along the cable implements filtering and wave analysis techniques to suppress noise prior to the virtual station streaming. These virtual stations can then be integrated directly into existing seismic networks using the SeedLink protocol.

This integration enables real-time data transfer and analysis, which is crucial for earthquake detection, localization and early warning systems. In this presentation, we describe the integrated interface features in the OptoDAS system, which facilitates the setup of the SeedLink data streaming. The station definitions and inventory profile are generated automatically based on the measurement setup, which is configured dynamically in the graphical user interface.

We present a case study of streaming data from a marine telecommunication cable offshore Svalbard, Norway. Our examples demonstrate the measurement and streaming-protocol setup on the DAS instrument. The streaming data are transmitted over a secured network connection to a data centre for archiving and further distribution.

In conclusion, we present our outlook for broad deployment of SeedLink streaming DAS units on a network of cables to achieve station coverage at scale in the ocean.

## AS25-0824

# Observation and inversion of dynamic and static deformation following dyke eruptive events using distributed FO sensing on Reykjanes Peninsula, Iceland

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Volcanic eruptions represent an eminent hazard in several areas of the world. Precursory activity such as deformation and seismicity offers opportunities to mitigate the risk. Scientific efforts aim at the earliest possible detection of such precursors. However, observational techniques are only partially suitable for a comprehensive real time monitoring. Remote sensing provides broad areal coverage but a limited temporal resolution and seismological networks record continuously but are spatially sparse. Distributed fiber optic sensing (DFOS) fills this observational gap by establishing spatially and temporally un-aliased seismic arrays along fiber optic cables dozen of kilometers long thus allowing for permanent monitoring of vast areas.

In this contribution, we evaluate recordings obtained with a commercial distributed sensing interrogator (iDAS) along a 20 km long telecommunication fiber optic cable on the Reykjanes Peninsula, SW Iceland, during an ongoing volcanic crisis. The recordings obtained since November 2023 comprise six volcanic eruptions. We demonstrate that the acquisition technique is able to resolve dynamic and static deformation associated to diking events prior to the volcanic eruptions. Our workflow uses edge-computing to decimate the densely sampled strain-rate recordings (1000 Hz, every 4 m). The decimated data is then transferred continuously to the computing center of GFZ in Potsdam, Germany, where source inversions based on Mogi and Okada models allow to follow magma progression from the reservoir until the eruption site. Our inversion results match well with observed eruption locations and show that seismological and geodetic observations with DFOS open a path for improved real-time monitoring of volcanic processes.

## AS25-0837

# Fiordland Seismological Sounding of Landslides and Earthquakes (FISSLE) — Monitoring Natural and Anthropogenic Phenomena in Milford Sound, New Zealand

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We introduce initial results from a distributed acoustic sensing (DAS) array deployed for approximately eight months between mid-June 2024 and late-February 2025 in the Fiordland region in the southwesternmost South Island of New Zealand. The Fiordland Seismological Sounding of Landslides and Earthquakes (FISSLE) array utilized dark telecommunications fiber running along the scenic highway SH94 between Te Anau and Milford Sound. We installed an iDAS interrogator at Milford Sound and recorded along 31.5 km of fibre from the coastline through the Homer Tunnel and to Christie Falls in Fiordland.

The high temporal (500 Hz) and spatial (4 m) resolution of the data acquired during the FISSLE experiment enable the analysis of weak seismic sources, such as low-magnitude earthquakes, but also other natural and anthropogenic processes including avalanches, rock falls, and even vehicle accidents. Here we present initial results from the experiment to illustrate how telecommunication fibres installed along a highway can aid in the monitoring of both deep-seated and near-surface phenomena in a remote area exposed to multiple natural and anthropogenic hazards.

## AS25-0873

# Unsupervised denoising of distributed acoustic sensing data via self-guided deep image prior

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Distributed Acoustic Sensing (DAS) has emerged as a powerful tool for capturing high-resolution seismological data, enabling precise detection of subtle vibrations generated by earthquakes, subsurface processes, and other environmental phenomena. Despite its potential, DAS systems produce large volumes of data characterized by a low signal-to-noise ratios, posing significant analytical challenges. Consequently, accurately distinguishing meaningful seismic signals from environmental or optical noise remains challenging, even for expert analysts and sophisticated processing techniques.

In this study, we investigate the effectiveness of Self-Guided Deep Image Prior (SG-DIP), a recent extension of the zero-shot Deep Image Prior (DIP) framework, which is an unsupervised deep learning approach for denoising DAS data without relying on reference images or explicit assumptions about noise characteristics. SG-DIP improves the conventional DIP framework by dynamically updating network inputs and introducing a novel self-guiding regularization term, effectively reducing overfitting to noise while preserving critical signal structures.

We evaluate SG-DIP on both synthetic DAS data and real-world DAS datasets collected near Haast, along the Alpine Fault, and Milford Sound, New Zealand. Our experiments demonstrate that SG-DIP consistently achieves promising performance compared to existing denoising methods, including those requiring supervised training or unsupervised adaptation tailored to specific datasets (non-zero-shot approaches). The results indicate that SG-DIP effectively recovers underlying seismic signals, leading to notable improvements in waveform coherence and overall data interpretability. These findings suggest that SG-DIP provides a robust, unsupervised denoising solution, enabling enhanced characterization of subsurface phenomena from DAS observations.

## AS25-0944

# Next-Generation Real Time Avalanche Monitoring: Distributed Acoustic Sensing for Multi-Site Integration and Advanced Environmental Noise Analysis

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Snow avalanches represent a major hazard in mountainous regions, particularly when snowpacks obstruct roads by burying vehicles or exposing traffic to successive avalanches during active cycles.

Since 2022, we have deployed Distributed Acoustic Sensing (DAS) powered systems to monitor avalanche activity along various road stretches, utilizing its technology to cover up to 170 km. Unlike traditional detection systems, which are limited to specific segments, the DAS-based alert system functions without being affected by visual limitations or harsh weather conditions. Our algorithm not only detects avalanches that impact the road and estimates the accumulated snow load but also records off-road avalanches, vehicles, and a range of environmental noises—such as sea waves, wind, quarry blasts, and local or teleseismic earthquakes.

Building on the previously published Holmbuktura avalanche dataset, we have broadened our analysis to capture events occurring further from the road and to incorporate environmental noise assessments. Additionally, we cross-referenced data from multiple sites in Norway, various fiber cable installation methods (hanging, buried, piped-buried etc.), and complementary instruments such as infrasound stations.

These findings highlight the system's reliability, low maintenance needs, and significant advantages over traditional methods, which are often expensive, limited in coverage, and vulnerable to environmental factors.

## AS25-0951

# Optimized DAS ambient seismic noise interferometry approaches for efficient, high-resolution investigation of the urban subsurface

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Local characterization and monitoring of the urban subsurface is critical for safe energy production and geohazard risk assessment. The interferometric analysis of anthropogenic seismic noise recorded on unused telecommunication fiber-optic cables (dark fiber) using Distributed Acoustic Sensing (DAS) is becoming attractive for high-resolution subsurface imaging in urban areas. Still, this approach remains underutilized due to the challenge of efficiently extracting coherent seismic energy from large-volume DAS data, characterized by complicated signal patterns resulting from the complex seismic noise field, unconventional array geometries and non-uniform cable coupling.

To address these challenges, we have developed efficient data exploration and selection tools, as well as signal enhancement approaches, resulting in an optimized ambient seismic noise interferometry workflow that maximizes coherent surface waves in urban DAS data. Automatic signal detection tools enable identifying problematic array sections (cable loops, poor coupling) or transient disturbances, and help isolate good-quality signals and opportunistic seismic sources such as trains. After noise cross-correlations, the quality of the resultant Virtual Shot Gathers (VSG) can still be highly variable. We develop categorization schemes using unsupervised clustering, which efficiently exclude transient and localized noise sources and retain high-quality VSGs that can be stacked for subsequent dispersion analysis and surface wave inversion. Our approaches are applied to DAS ambient noise datasets recorded along dark fibers in busy cities such as Berlin (Germany) and Istanbul (Turkey). Ultimately, our approach results in enhanced, high-resolution shear-wave velocity models of the urban subsurface at a local to regional scale, with reduced uncertainties and increased depth of investigation.

## AS25-0973

# Enhancing Seismic Event Location with DAS: Insights from SED and BedrettoLab

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We explore how Distributed Acoustic Sensing (DAS) data is being integrated into the real-time seismic monitoring workflows of the Swiss Seismological Service (SED) and the Bedretto Underground Laboratory for Geosciences and Geoenergies (BedrettoLab). From national-scale monitoring to high-resolution imaging of fluid injection experiments, we demonstrate how DAS extends the capabilities of existing seismic networks across multiple scales. Temporary DAS deployments across Switzerland have been incorporated into SeisComP, converting raw DAS measurements into strain and velocity timeseries for seamless integration with conventional seismic data.

Building on this, we now leverage DAS to refine the location of the largest events in the Bedretto experiment FEAR1 and establish a pseudo ground-truth (or underground truth) against which we calibrate our locator configuration. This improves event location accuracy and informs the development of next-generation locators that merge DAS with conventional seismic instrumentation. We present case studies showcasing how DAS enhances event detection, characterization, and real-time automated monitoring.

A key example comes from a 42-meter borehole section at BedrettoLab during hydraulic stimulation for FEAR1, where a single-mode loose fiber-optic cable was interrogated at 80 cm intervals with a 4 m gauge length and 4000 samples per second, significantly improving real-time tracking of induced seismicity. Additionally, we evaluate DAS performance across different seismic conditions by analyzing noise characteristics and amplitude decay. We highlight key challenges, lessons learned, and future directions, including improving DAS-based monitoring workflows and exploring its role in earthquake early warning.

## AS25-0993

# Immediate and High-Precision Hypocenter Determination for Earthquake Early Warning in Bullet Train Systems Using Distributed Acoustic Sensing

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Earthquake Early Warning (EEW) systems for the Bullet Train (Shinkansen) in Japan can issue warnings based on data from a single observation point, even when only the P-wave is detected. While this maximizes lead time, it results in significant estimation errors (epicentral distance: half to double, back azimuth: ±30º). Distributed Acoustic Sensing (DAS) enables high-density seismic observations, allowing for rapid and precise hypocenter determination, significantly reducing errors compared to single-station EEW methods. This study explores the feasibility of integrating DAS into EEW by utilizing fiber-optic cables along the Kyushu Shinkansen to analyze strain-rate waveforms, detect P-waves, and determine earthquake hypocenters. P-waves were detected using STA/LTA (Allen, 1978) across multiple channels, and hypocenters were determined using HYPOMH (Hirata and Matsu'ura 1987). To achieve rapid estimation, we updated the hypocenter location each time P-wave detection points increased by 20. For earthquakes with an epicentral distance of less than 50 km, the hypocenter was determined within 10 km of the Japan Meteorological Agency (JMA)-reported location within 2 seconds of the initial P-wave detection. Furthermore, the magnitude was estimated using an empirical law based on the maximum strain rate within 2 seconds, with an error of ±0.5 relative to JMA values. These findings suggest that a DAS-based EEW system has strong potential for rapid and accurate earthquake detection, particularly for near-field earthquakes beneath densely populated areas, where lead times are short, and the risk of significant damage is high.

## AS25-1096

# Real-time Testing of DAS-based Earthquake Early Warning in Northern California: Design and Implementation

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Distributed Acoustic Sensing (DAS) technology can potentially extend seismic network coverage, improving real-time earthquake detection and Earthquake Early Warning (EEW). In the current ShakeAlert EEW system on the U.S. West Coast, regions at the edges of the seismic network and areas with known active faulting could benefit from the additional DAS observations. Applying DAS to submarine fiber-optic cables, for example, could enable earlier and more precise detections for offshore events, such as earthquakes in the San Gregorio Fault zone and the Mendocino triple junction in Northern California.

To maximize the potential of DAS for EEW, we have developed an algorithm fully utilizing DAS's dense spatial sampling. This algorithm integrates a machine-learning-based seismic phase picker, a grid-search event locator, and an empirical magnitude estimation method. Using parallel processing and GPUs, we optimized the workflow to meet real-time streaming requirements, ensuring processing speeds comparable to existing EEW systems. The independent algorithm generates event messages that can be ingested as point-source events by ShakeAlert in a similar fashion to how EPIC point-source events are integrated into ShakeAlert. We envision introducing new modules to associate detected events from the DAS arrays with detections from traditional seismic stations at the waveform pick level. This real-time information can be used to jointly solve for the earthquake location. We are currently testing the algorithm in real-time in the Monterey Bay region with data from the permanent DAS deployment "SeaFOAM". This work serves as a foundation for incorporating potential future DAS arrays into ShakeAlert, to enhance EEW.

## AS25-1278

# Fault system and shallow seismicity in the Pyrenees foothill from nodal and DAS seismic arrays

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In the western foothill of the Pyrenees in France, the Arette region is known for a shallow 1967 earthquake that destroyed 80% of the village. No precise clues on the fault at the origin of this earthquake exist. A previous deployment of 200 seismic stations by the Observatoire Midi-Pyrénées de Toulouse (OMP) revealed very shallow seismicity in the sedimentary cover, potentially associated with fluid circulation, which could facilitate earthquake nucleation. In a new study dedicated to constraining the fault system and the shallow seismicity, the OMP and Mantle8 company deployed a 2000 meters-long optic fiber cable specifically designed for geophysical measurements, as well as a dense array of 58 nodes over a 2x3 km2 area. The fiber was set in a harsh terrane with 200 meters+ positive elevation, extensive vegetation, and partially buried in a trench over half its length. We recorded on the fiber ~30 good quality events over a 10-day period, among which 2 are located right underneath the cable. The waveform analysis suggests the presence of 2 anomalies in the southern portion of the fiber, spatially correlated with lows in the topography, and possibly related to site, fault, rugged terrane, and/or fiber coupling effects. Further insight will be gained from modeling and active seismic refraction profiling. We will also report on the result of relocating local microearthquakes as well as P- and S-wavespeed model reconstruction from the joint nodal and DAS arrays.

## AS25-1302

# The fiber-optic seismic monitoring network of north-eastern Italy

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Recent advances in Distributed Acoustic Sensing (DAS) technology allow the transformation of existing fiber-optic telecommunication networks into dense seismic sensor arrays. In collaboration with Friuli-Venezia Giulia region and the regional telecommunication provider, the National Institute of Oceanography and Applied Geophysics (OGS) has launched a project to integrate DAS into the seismic monitoring infrastructure of North-Eastern Italy. This initiative exploits dark fibers to complement the existing network with high-resolution strain measurements, enhancing earthquake detection, early warning capabilities, and geohazard assessment.

A pilot experiment conducted over a 20 km stretch of fiber successfully demonstrated the feasibility of this approach in urban environments, capturing both anthropogenic and seismic signals, including teleseismic events. Following this proof-of-concept, a regional deployment plan is being implemented within the PNRR ITINERIS framework. Five strategic nodes have been identified for DAS interrogators, selected based on seismic hazard distribution and network infrastructure.

The integration of DAS data into the regional seismic monitoring system (SMINO) is expected to refine earthquake source parameters, improve the resolution of ground motion measurements, and expand real-time monitoring capabilities. This represents one of the first large-scale DAS deployments for seismic applications in Europe, paving the way for future cross-border seismic networks and multi-hazard monitoring initiatives.

## AS25-1319

# The SUBMERSE consortium – paving the way for continuous fibre-optic monitoring with submarine telecommunications cables

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In the last years, fibre optic sensing methods have been experimentally demonstrated to be suitable for monitoring Earth System parameters in submarine cables. The SUBMERSE project (SUBMarinE cables for ReSearch and Exploration) aims to develop blueprints for using telecommunication fibre optic cables as sensors by attaching fibre optic interrogators at selected landing stations, also building a data infrastructure for both temporary storage of full resolution data and permanent archival of reduced data sets.

SUBMERSE has demonstrated the coexistence of Distributed Acoustic Sensing (DAS) with active telecommunications traffic on the same fibre and deployed state-of-polarisation (SOP) measurements synchronised with an atomic clock on a submarine cable near Svalbard. In collaboration of scientific institutions and instrument manufacturers, we have enabled real-time streaming of DAS data following the standard Seedlink protocol, which allows straightforward integration into existing workflows at earthquake observatories (presentation by Ch Evangelidis). We have developed an automated, machine-learning-based algorithm for analysing earthquake waveforms (presentation by H Xiao), and measuring ocean surface gravity waves using seafloor DAS recordings (presentation by D Schlaphorst).

Geopolitical events and incidents involving suspected targeting of critical submarine infrastructure have posed challenges to international data sharing. While adhering to the FAIR principles, we address the evolving complexities of sharing data that may contain sensitive information alongside valuable research content. This presentation will detail the activities, achievements, and challenges of SUBMERSE, which strives to develop a pilot research instrument and provide a blueprint for continuous monitoring of the Earth systems across and between continents.

## AS25-1340

# Monitoring groundwater flow using fibre optic sensing

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Locating and monitoring groundwater flow is key to understand the health of aquifers, and possible pathways for groundwater flooding events affecting citizens and infrastructures.

In this work, we are going to test the potential of Distributed Acoustic Sensing (DAS) on telecom fibres for monitoring groundwater flow. Telecom fibre cables are readily available in many areas where groundwater monitoring is key, such as densely populated cities and major roads, and DAS offers the possibility to achieve great spatial resolution (down to 1 m) with little deployment cost (provided access to the fibres).

Firstly, we test the capabilities of DAS compared to traditional seismometers. We use records from a dense deployment over an underground, water-filled cave in County Roscommon, Ireland recorded in 2020. By rotating and differentiating the horizontal seismic velocities, we simulate the geometry, spatial averaging and strain rate from a virtual DAS following the seismometer profiles. Secondly, we use the Amplitude Source Location Method to track the location of the tremor on both seismometer and virtual DAS records to assess virtual DAS performance.

Finally, we will present the results from ongoing DAS surveys on both dark and lit telecommunication fibres in Ireland to map groundwater flow, targeting rivers along the fibre path for benchmarking as well as karstic areas of past groundwater flooding. This experiment will be one of the earliest uses of DAS to locate and monitor groundwater flow, setting the stage for the use of fibre networks as a tool for high-resolution, long term aquifer and flood monitoring in urbanised areas.

## AS25-1387

# Automated Real-Time Avalanche Alert System Using Distributed Acoustic Sensing

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Snow avalanches represent a significant threat to communities in mountainous areas. Specifically, the risk of avalanches restricts freedom of movement for those dependent on roads that are prone to these hazards. Avalanche alert systems play a crucial role in improving road safety, as early detection can prevent vehicles from entering hazardous areas. However, traditional systems (e.g., radar) face challenges such as limited coverage and difficulty in accurately determining whether an avalanche impacts the road.

Distributed Acoustic Sensing (DAS) offers a promising solution to address these challenges. We have developed an automated avalanche alert system using DAS, which has been refined over three winters to become a reliable tool for detecting avalanches that impact roads. The system employs advanced signal processing techniques to differentiate avalanches from other seismic or acoustic events. Furthermore, it provides real-time tracking of all vehicles on the road, offering vital information for search and rescue operations.

Our solution is based on edge computing and requires only a 4G connection. It is integrated with the national Traffic Control system, automatically issuing alerts for road-blocking avalanches and supplying information on the number of vehicles in the danger zone.

## AS25-1419

# Monitoring deep-seated landslide dynamics using borehole distributed acoustic sensing

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Deep-seated landslides are complex geological phenomena that pose significant damage to infrastructure and human safety. Monitoring the dynamics of these landslides is critical for early warning and risk assessment. In this study, we employ Distributed Acoustic Sensing (DAS) technology to investigate internal deformation of a deep-seated landslide in Lantai, northern Taiwan, using a borehole fiber-optic cable installed across multiple slip zones. DAS transforms fiber-optic cables into dense seismic sensor arrays, detecting ground motion along their length and enabling precise monitoring of subsurface displacements and slip activity. Preliminary results show that DAS effectively captures the accelerated movements and recurring stick-slip events modulated by heavy rainfall of typhoons during the observation periods. The periodic stick-slip events, which cannot be detected by surface geophones, indicate velocity-weakening frictional characteristics near sliding interface between soil and bedrock around 20 meters depth, shedding light on the mechanisms behind landslide movements. This innovative approach provides a promising tool for real-time monitoring of deep-seated landslides, offering valuable data for risk mitigation and disaster preparedness.

## AS25-1460

# Optical interferometry cable-based seismic detection in the Pacific Ocean

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We present optical interferometry-based measurements on a seafloor cable in the Tasman Sea between New Zealand and Australia. Previously, using this technique, we demonstrated detection of earthquakes, ocean currents, and storms using a seafloor cable in the Atlantic Ocean as an array of environmental sensors [1]. In this new work, we show the results from interferometry measurements in a much higher seismically active region of the world. In the first month of our measurements alone, tens of events were detected with epicentres 10–100 km away from the cable. This very high seismicity of the region combined with the elbow-shaped cable route offer a unique opportunity to accelerate the research on the capabilities of seafloor cable-based sensing techniques.

We will present results from several month-long ultra-stable interferometric measurements, including detections of local and tele-seismic earthquakes, as well as ocean currents. Additionally, we will discuss results from tests of submarine cable response to seismic waves, performed in a controlled environment at NPL, providing crucial information for achieving calibration of cable-based earthquake detections on the seafloor.

This work is an important step towards filling the data-gap from the ocean floor and integrating this novel type of sensing solution with existing land-based seismometers used for the detection of submarine seismic events and for tsunami early warning.

[1] Marra G, et al., "Optical interferometry-based array of seafloor environmental sensors using a transoceanic submarine cable", Science, 376 (2022), https://www.science.org/doi/10.1126/science.abo1939.

## S07 Anthropogenic Seismicity

### AS25-0016

# Seismological Evidence for the Existence of long-distance hydrological Channel and its Implication for Fluid Overpressure in Southern Sichuan, China

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Increasing seismicity in southern Sichuan is suspected to be linked to hydraulic fracturing stimulation for shale gas extraction. Induced earthquakes resulting from fracturing operations at nearby wells can be verified using in-site fracturing data, while remote-induced factors are hard to prove. In this study, the high-resolution velocity and velocity ratio are imaged using dense passive array data. The models reveal a 15 km long anomaly belt of low Vs and high Vp/Vs in the Cambrian strata in southern Sichuan. Through investigating the focal mechanism solution, fluid overpressure of events near the belt, and the seismicity, we propose that this anomaly belt may represent a hydrological channel saturated by overpressured fluid. The occurrence of the Ms 4.7 Gongxian earthquake confirms for the accumulation of high pore fluid pressure at the end of this hydrological channel. It should be emphasized that due to a lack of in-site hydraulic fracturing data, we argue that fluid diffusion, aseismic slip, and pore-elastic effects, may contribute to the stress accumulation on the seismogenic fault at different stages. Another similar anomaly to the southwest may have similar properties to this channel, with a moderate earthquake risk at its end. Overall, blocking such channels is of utmost importance in the seismic risk management in the study area.

## AS25-0040

# Enhancing Event Discrimination with Infrasound: Differentiating Tectonic Events from Quarry Blasts in Southeastern Brazil

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Discriminating tectonic events from artificial ones poses a significant challenge, particularly when both sources are small and geographically close. This issue is common in regions with quarries for rock blasting and tectonic seismic activity. This study focuses on distinguishing tectonic events from quarry explosions by integrating seismic and infrasound data collected from stations in Sete Lagoas, Minas Gerais, southeastern Brazil. The region experiences low-magnitude natural and anthropogenic events, which are often difficult to differentiate. Properly identifying these events is crucial for understanding anthropogenic processes, assessing risks, forecasting impacts, and mitigating environmental damage.

The NDC-in-a-Box software, along with SEISAN and SeisComp software, was used to evaluate signals, correlations, locations, and magnitudes. The application of infrasound technology plays an important role in event discrimination by detecting acoustic signals typically associated with quarry explosions, while low-magnitude natural tectonic events ($M < 3$) are generally characterized by the absence of such signals. Additionally, focal mechanism determination contributes to the characterization of stress orientation and fault plane solutions. This comprehensive approach, combining seismic and infrasound technologies, enhances the ability to identify seismic patterns, differentiate between tectonic and artificial sources, and deepen the understanding of local phenomena and their environmental implications.

## AS25-0076

# Artificial Water Reservoir Triggered Seismicity (RTS): A Global Review

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Anthropogenic activities, such as gold/coal mining, natural gas/oil production, harnessing geothermal energy, filling artificial water reservoirs etc., can lead to the triggering of earthquakes. Among all these anthropogenic activities, RTS is the most prominent having been reported from hundreds of sites. At least at 5 sites, earthquakes exceeding M 6 have occurred. The most important correlate for RTS is the height of water column in the reservoir. The common characteristics of RTS are useful in ascertaining whether the observed seismicity in the vicinity of an artificial water reservoir is RTS or natural seismicity. The lack of knowledge of the physical properties of rocks and fluids in the fault zone does not permit comprehending the genesis of RTS. The Koyna Dam site in India is found to be a very suitable location for putting a deep borehole to learn the physical properties in the earthquake source zone before, during and after the occurrence of the seismic event. Among the salient findings is understanding of the nature of the stress field in the source zone in the Koyna region.

## AS25-0162

# Identifying fracture networks reactivated during fluid operations: case study from Coso Geothermal Field, California

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Identifying the faults and fractures reactivated during geothermal field operations can be challenging, especially considering the sites' generally complex geology and stress fields. However, knowledge of which fractures rupture when provides important insight into the fluid flow within a field. The Coso Geothermal Field (CGF) in California experiences both natural and induced seismicity due to its tectonically active setting and 30+ years of fluid extraction and reinjection. Additionally, the induced seismicity can be correlated to both long-term normal production and the rapid pore-pressure increase during shorter-term operational pauses, or so-called shut-ins. Here, we analyze 15 years of daily operational data and seismic waveforms recorded on 24 local seismic stations with the goal to identify the structures reactivated during shut-ins at the CGF. Using a catalog of over 60,000 earthquakes with moment magnitudes between -0.4 and 3.8, we first relocate events using waveform correlated differential times and compute focal mechanisms. While shut-in seismicity generally occurs in different regions compared to the normal production seismicity, we find no significant difference in their focal mechanisms, implying similar stress fields are acting during both types of operations. Furthermore, we combine the focal mechanisms, earthquake relocations, and waveform similarities to infer fault planes within the field to minimize the location uncertainties caused by using a simple 1D velocity model in a geologically complex area. Understanding the relationship between operational parameters and the reservoir's seismic response can reveal critical factors that influence the stress field and the reservoir's productivity, guiding operators regarding future drilling sites.

## AS25-0181

# Prediction of induced seismicity with machine learning

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Seismicity induced by fluid injection (e.g. enhanced geothermal systems, CO2 storage) remains a significant concern of risk for communities and industry as it may cause structural damages and economic losses. In some cases, this can even lead to the immediate shutdown of the project, as observed in Pohang, South Korea (2017), after inducing a magnitude 5.5 earthquake. Consequently, it is crucial to develop new strategies to anticipate and mitigate the seismic risk resulting from these geothermal operations. In this work, we present an innovative machine learning-based approach to forecast the seismicity induced during geothermal operations. It leverages the time series of various injection parameters, such as flow rate and wellhead pressure, to capture their complex relationship with seismicity rate using a gradient boosting algorithm. Once our model is trained, it is then possible to estimate the future number of induced earthquakes, on a fixed time scale of interest. We apply our method to several stimulation phases from 2000 to 2005 of the Soultz-Sous-Forêt (France) enhanced geothermal system, which triggered important rises of the seismicity. By training our model on the first days of the stimulations, we could forecast the number of future induced earthquakes at a fixed time horizon. This work paves the way to new application prospects, such as the prediction of microseismicity within ongoing geothermal operations, for example at the Rittershoffen power plant, located just 6 kilometers away from Soultz-Sous-Forêts.

## AS25-0210

# Role of tectonic features in anthropogenic seismicity – cases from Poland and Vietnam

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Tectonic features play an essential role in anthropogenic seismicity. Reactivating faults with water fluctuations in artificial reservoirs or injection in geothermal fields is responsible for relatively strong earthquakes such as the M6.6 Koyna event in India or the M5.5 Pohang earthquake respectively. However, it is mainly related to human-triggered seismicity, while the role of tectonic features in induced seismic activity is more complex. We will present anthropogenic seismicity cases related to reservoir impoundment (RTS), underground and open-pit mining. Water impoundment and fault activation in Song Tranh2, Lai Chau (both Vietnam) and Czorsztyn in Poland, mining-triggered seismicity controlled by fold hinge zone in Bobrek Mine, inactive fault role in the Legnica-Głogów Copper District rockburst and Kleszczów Graben reactivation of some of the pre-existing faults, partly due to open pit mining exploitation in Bełchatów mine will be presented. Analyses of the seismic process related to these cases allow us to unveil the role of tectonic features in anthropogenic seismicity. In the case of Song Tranh2, Czorsztyn, Bobrek and Bełchatów mines, tectonic features are considered to be tectonically active, which may lead to the triggering of seismic events, while in Lai Chau reservoir influence on fault activation is limited. On the other hand, an inactive fault zone in Rudna mine acts as a weak zone, and rockburst initiated as a reverse faulting event may be induced along a pre-existing fault. It happened despite the lack of proof in the available data for reactivating the tectonic processes in the area that was considered inactive.

## AS25-0289

# Seismic and aseismic phenomenon related to fluid manipulation in the Cerro Prieto Geothermal Field

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The Cerro Prieto Geothermal Field (CPGF) has been producing electricity from geothermal fluids for the last 50 years. Since the CPGF is located in the Mexicali Valley, in the southern part of the San Andreas system, on the border between tectonic plates, characterized by active tectonism, hydrothermal processes, volcanism, and high seismic activity, it is quite difficult to distinguish if any part of seismicity is related to anthropogenic activity.

Since fluid extraction began at the CPGF, Majer and McEvilly (1981, 1982), Fabriol and Munguía (1997), and Urban and Lermo (2012) noted some relation between microseismicity and extraction/injection activity, while other authors discussed the possibility that strong earthquakes were possibly triggered by the fluid extraction at the CPGF, *i.e.,* Imperial, Ml 6.6, 1979; Victoria Ml 6.1, 1980 (Glowacka and Nava,1996); and El Mayor Cucaph, Ml 7.2, 2010 (Trugman *et al.*, 2014; Samsonov *et al.*, 2017).

In contrast to the above situation, the relationship between fluid extraction and subsidence was exhaustively studied (*e.g.*, Glowacka *et al.,* 1999, Sarychikhina *et al.,* 2025). The phenomenon of creep and slip events was observed on faults limiting the subsidence area (*e.g.*, Nava and Glowacka, 1999; Sarychikhina et al., 2015). Subsidence modeling (*e.g.,* Glowacka et al., 2005, Gallardo *et al.,* 2025) reveals the value of induced stresses and allows its comparison with tectonic stresses.

This work summarizes and analyzes 50 years of data to determine if the aseismic phenomenon observations can help identify conditions that allow induced and triggered seismicity to occur.

## AS25-0335

# Multiscale Seismic Indicators of Damage Accumulation and Stress State Evolution

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Understanding fault damage evolution and stress redistribution is critical for seismic hazard assessment, particularly in Anthropogenic Seismicity (AS). While AS results from controlled technological activities, its seismic response remains an unpredictable by-product. Variability across different settings highlights the complexity of damage accumulation and stress transfer, influenced by site-specific geological conditions and operational parameters. Assessing how stress perturbations, and fault properties interact is essential for understanding rupture processes.

This study introduces seismic regularity coefficient (dc) and seismic strain dynamics (SSD) as multiscale indicators of fault damage and stress evolution. dc quantifies the organization of seismicity in terms of interevent time, distance, and magnitude. A decreasing dc suggests the emergence of more regular seismic patterns, potentially reflecting a shift toward stress homogenization, while an increasing dc indicates greater variability in seismicity, associated with enhanced microfracturing in process zones of small fractures. SSD captures variations in strain release, offering insights into stress redistribution and subcritical damage accumulation.

By integrating laboratory experiments and real seismicity data, we track these parameters across AS environments as reservoir impoundment, mining, and geothermal energy production. We identify three damage stages: nucleation, where microfracturing initiates; hardening, marked by peak fracturing and lowest dc; and failure, culminating in rupture. Our findings show that dc and SSD systematically indicate strain localization and the transition from distributed damage to system-size failure preceding larger rupture events. Moreover, the duration of final damage stage scales with earthquake magnitude, suggesting that seismicity metrics provide insights into the progressive localization of strain and fault failure processes.

## AS25-0398

# Triggered Seismicity in Southeastern Brazil due to Stress Relief from Large-Scale Limestone Extraction

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On August 14, 2011, an earthquake of magnitude 3.2 (MMI IV-V) occurred near Funil Reservoir Power Plant and open pit limestone mines, both located close to Ijaci town, SE Brazil. The main shock was followed by three other events of similar magnitudes within three months. We study the seismicity near Ijaci, and its possible relationship with the reservoir impoundment, the mining activity, and the lowering of the water table. We use data from a local 7-station seismic network and piezometer measurements. More than 1000 events were detected, of which 500 were classified as tectonic, and the rest were explosions in four limestone quarries that operate close to the reservoir and daily feed one of the largest cement plants in Brazil. The local karst relief sustains a large aquifer at the bottom of the pits and is responsible for an average outflow of 350 $m^3$/hour at Mina Sul pit. The mining activities and the filling of the Funil reservoir occurred at the end of 2002. Focal mechanisms determined by polarities and waveform inversion indicate reverse faults and a compressive tectonic regime in the Ijaci area. Piezometer measurements showed no direct connection between the lake and the bottom of the pit; the pumping that lowers the water table has little influence on the stress regime. The event locations, focal mechanisms, and volume of extracted material suggest an association of this seismicity with the extraction of limestone, which is equivalent to approximately 60 million tons (5.9x10 N) of load relief.

## AS25-0558

# Source parameters analysis of the induced earthquakes at Hengill geothermal field, Iceland

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The Hengill geothermal field, located in southwest Iceland at the boundary between the North American and Eurasian plates, has been harnessed for electricity generation and heat production since the late 1960s. This region hosts Iceland's two largest geothermal power plants, Nesjavellir and Hellisheiði. In total, there are 76 wells in these facilities, reaching a maximum depth of 2 km. Seismic activity includes both natural and induced events. Induced earthquakes were detected already during the initial drilling and testing phases of the boreholes and increased as the number of wells grew and injection operations expanded.

This study is carried out in the framework of the PRIN PNRR DIRECTIONS project in which a neural network called PreD-net is being developed and tested for the identification of foreshocks of the larger magnitude induced events. PreD-net analyzes statistical features (e.g., b-value, CoV, fractal dimension,…) starting from the seismic catalogue. In this work instead, some seismological features are analyzed such as stress-drop, apparent stress, Vp/Vs-ratio variations, to investigate the physical model that can help explaining the preparation and triggering phase of the largest induced events. Meanwhile, we also investigate if foreshocks and aftershocks have similar kinematic and dynamic source parameters.

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## AS25-0653

# Mitigation of seismic activity using preaconditioning technique by blasting on panel caving

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The in-situ stress state of a rock mass is primarily determined by gravity and tectonic forces. Mining operations disrupt this equilibrium, creating localized stress concentrations and reductions that can trigger increased seismic activity. The panel caving technique, in particular, inherently generates excessive stress within the surrounding rock mass, leading to microfracturing and associated seismicity. We analyzed the frequency and intensity of anthropogenic seismicity induced by panel caving, both with and without preconditioning through blasting, at the Andina mine in Chile. Our results suggest that a large, competent rock mass without preconditioning exhibits mining-induced seismicity characterized by a greater number of higher magnitude events compared to when intensive preconditioning is employed. This effect is especially pronounced at deeper levels where the rock is more competent.

## AS25-0744

# Importance of Accurate Earth Models and Network Geometry for Earthquake Location in Induced Seismicity

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Since the beginning of the 21st century induced seismicity is an important topic due to the increased number of **industrial** well operations. Such operations are usually within an overlying, sedimentary basin structure, and are shallow compared to the depth of basement rocks where natural seismicity occurs. One of the most challenging problems is reliable hypocenter location. In particular, the resolved depth of earthquakes is highly dependent on the velocity model used for the subsurface and on the seismic network geometry. A regional seismic network typically cannot overcome these problems, mostly because: (a) the network does not have a small station spacing with respect to the target depth of the human activities, and (b) accurate 3D velocity models for the basin and basement structures are not available.

We developed an approach using sonic log, check-shot data and tomography results for the Midland basin, Texas, to investigate the sensitivity of **hypocenters** to details of the velocity model and to location procedures. In a subarea of the basin where the network geometry is as dense as 5 km inter-station distance, and using at least 5 stations to locate an event we find that including stations at distances greater than 12 km gives a strong effect of the basement velocity on locations. When using reduced velocities for the basement and stations at larger distances, hypocenters move deeper in the basement. When there are high-impedance velocity contrasts either inside the basin structures or at the basin basement interface, artifact, horizontal streaking of earthquake location can occur.

## AS25-0959

# Challenges in setting up of a Borehole seismic network at Koyna-Warna: A decade of experience of micro seismic observations

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The Koyna-Warna region located in the west coast of India is a unique example of Reservoir Triggered Seismicity, where earthquakes have been occurring in a restricted area of ~ 30x20 sq. km since the impoundment of Koyna reservoir in 1962 and the Warna reservoir in late 1980's. The earthquake of M 6.3 that occurred on 10 December 1967 is considered as one of the largest RTS event so far. The continued seismicity at shallow depths within 10 km in this region for the past six decades was monitored through surface seismograph networks installed from time to time and the location accuracies were improved by enhancing the seismic network capabilities by various up gradations. As part of a deep scientific drilling program, exploratory boreholes were drilled up to depths of about 1500 m and instrumented with tri-axial borehole seismometers. The installation of the borehole seismic network of eight stations posed lot of challenges starting from the selection of seismometers as no commercially available borehole seismometers were available to install up to depths of about 1500 m and transmit undistorted data. In addition to the core drilling challenges to drill into hard rock the deviation of the boreholes and cable strengths for the installations and finding the orientations of the borehole seismometers were some of the challenges apart from the installations. The details of the challenges faced during the experimental stage and the continued operation of the seismic network along with results like improved detection and earthquake locations will be presented here.

## AS25-1055

# Seismological characterization of the March 3, 2018, Maceió (Brazil) earthquake and its link to subsidence

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Ground subsidence processes, both natural and human-induced, influence metropolitan areas worldwide. Maceió, Brazil, has seen an increase in sinkhole development and infrastructure damage since a magnitude 2.4 earthquake occurred on March 3, 2018. This seismic event occurred near a deep salt mining operation. We relocated the earthquake using data from the Brazilian Seismographic Network, with station distances ranging from 58–289 km, and processed seismic records with a Wiener and a 4–8 Hz band-pass filter. The HYPO71 code from the SeisComP package estimated the earthquake's location, utilising P and S wave arrivals from the four closest stations. We estimated the focus depth at 1 km near Mundaú Lagoon, where over 200 cm of accumulated subsidence occurred. The epicentre and depth uncertainties were 3 km and 4 km, respectively. Using P-wave polarities and amplitude ratios to perform a focal mechanism inversion with the FOCMEC package, we found that the solutions indicate normal faulting along NE-oriented fault planes. We also inverted for the full moment tensor with the ISOLA package for three stations with good surface wave records, with the best-fitting results also indicating a normal faulting mechanism at 0.7 km depth with a small DC component of 4.7, high CLVD of -66.2, and VOL (=ISO) of -29.1. These results suggest that this main event is associated with subsidence primarily linked to removing localised, deep-seated material where salt is mined. This work contributes to Project TSHAPS (REF 541685934) supported by Program FCT—Aga Khan.

## AS25-1114

# Seismicity Induced by Open Pit Mines—Starting a Worldwide Compilation

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Seismicity induced by water reservoir, fluid injection and underground mines are widely known phenomena that have been studied for decades. However, seismicity induced by crustal unloading in open-pit mines are seldomly reported in the literature. The worldwide HiQ database of induced seismicity reports only four cases related to open pit mining (OPM), also known as "quarrying". The majority of mine-induced seismicity relate to deep underground mines and magnitudes have not exceeded 5.5 Mw

Here, we compiled other OPM cases from the literature and yet unpublished results. A total of 14 cases have been found with maximum magnitudes ranging from 2.5 ML to 5.2 Mw. 12 cases are most probably induced by the crustal unloading from the excavation, and 2 are not clearly related to the open pit. The correlation of maximum magnitudes with the sizes of the open pit (area, depth and volume) shows the best correlation coefficient (0.6) for pit area (length x width). Correlation with the total load of the excavated rocks (~ excavated volume) is 0.5. The correlation with pit depth has the lowest correlation coefficient of 0.3. These results are similar to the pattern of Mmax for water-reservoir seismicity found in the HiQ database which also showed best correlation with the total area of the reservoir and lower correlation with water (or dam) height. The planned increased exploration of critical mineral resources, such as copper, should encourage more studies of OPM seismicity.

## AS25-1133

# New insights on physical mechanisms governing the reservoir-induced seismicity in the High Agri Valley, Southern Italy

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The High Agri Valley, an intermontane basin situated in the axial part of the Southern Apennines, is a region of geophysical interest due to its high seismic hazard and the co-existence of natural and induced seismicity. This study aims to investigate and enhance the understanding of the driving processes behind reservoir-induced seismicity, which occurs along the Monti della Maddalena Fault System (MMFS) and which has been linked in the literature to the Pertusillo Lake. The physical mechanisms underlying the seismicity production, mainly clustered southwest of the Pertusillo water reservoir, have not been completely understood, but a significant correlation with seasonal water level fluctuations has been demonstrated. Furthermore, the role of aquifers in triggering seismicity cannot be disregarded, especially considering that some seismic events also extend toward the northern sector of the MMFS.

We present the initial results obtained from a Finite Element Method (FEM)-based numerical model designed to simulate the stress and strain fields induced by seasonal fluctuations in lake water levels, while also accounting for potential contributions from nearby aquifers. This model incorporates geological and geophysical data from the area and considers fault structures already known from literature and those retrieved from an extensive seismic dataset of numerous micro and small earthquakes recorded from 2016 to 2023.

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## AS25-1148

# Microseismic source properties from geothermal stimulations at Cape Station, Utah

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Microseismicity is produced abundantly by enhanced geothermal systems (EGS) and monitoring their properties is crucial for monitoring the hazards of EGS operations. The use of fiber optics and distributed acoustic sensing (DAS), which are able to be deployed down high-temperature wells, have greatly enhanced EGS microseismic catalogs; however, due to issues such as having only a single component, amplitude saturation and uncertain cable coupling, it is often preferable to measure source properties, such as earthquake magnitude and focal mechanism, from surface arrays. We compile a catalog of thousands of events from EGS activities at Cape Station, Utah, involving multistage stimulations on multiple horizontal wells. The microseismicity starkly illuminates previously unseen structures. Using a combination of surface arrays and DAS fiber data, we estimate source properties such as focal mechanisms and stress drop, and investigate the mechanisms of seismicity localization and migration through the well area.

## AS25-1150

# A possible relation between the subsidence rate of Mexico city and seismicity

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Over the last century, Mexico City has been subsiding, currently at a rate of several tens of centimeters per year. This phenomenon is commonly attributed to the depletion of underground aquifers, demonstrating a direct relationship between the subsidence rate and the thickness of the upper aquitard. Data from the C-SAR instrument onboard Sentinel-1 satellites were used to determine subsidence rates over Mexico City between November 2016 and March 2023. These rates were then compared with seismic activity data retrieved from the seismic catalog provided by UNAM. Our analysis revealed that, on average, an increase in the subsidence rate precedes an increase in seismic activity by several months. The metropolitan area of the Valley of Mexico rests on clay-rich Quaternary deposits, which constitute the upper aquitard, and were initially heavily saturated with saline porewater. Lowering water levels in the aquifer reduces the interstitial water pressure, leading to consolidation of the aquitard and, consequently, surface subsidence. We hypothesize that the subsidence does not fully compensate for the loss of pressure, thereby preconditioning the ground for a stronger response to seismic ruptures.

## AS25-1307

# Groundwater extraction as trigger mechanism of the Anker seismicity?

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Since August 2017 there has been an increase in earthquakes around Anker settlement, North West of Namibia. Data from temporary seismic stations deployed for three months in June to September 2018 and one year from November 2021 to November 2022 led to recording of over 27000 earthquakes with magnitudes -0.9 to 4.6 $M_L$. This unusual increase in earthquake activities led to temporary relocation of the school and some community members. The water supply for the Anker community is through groundwater extraction in fractured aquifers. Historical groundwater extractions indicate significant changes in rest water levels of boreholes in Anker and the surrounding areas which might have contributed to unexpected increase in earthquake activities. Historical Rest Water Levels (RWL) in 21 boreholes in production for 3 decades (1986–2018) around the study area indicated a significant drop of rest water levels of over 17 m in Anker due to groundwater abstraction. In Khorixas, which is South of Anker, showed the highest drop in Rest Water Level of over 55 m. The boreholes data in Erwee, North of the study area showed a drop of Rest Water Level of just over 2 m. New insights supports presence of a nearby geothermal springs implies the possible involvement of fluids in the seismic process (Angombe et al, 2023) as evident from the geometry and depth of the swarm. The contribution of groundwater depletion might be minimal as the depth of boreholes are less than 200 m and hence the resultant change in Coulomb's stress could be insignificant.

## AS25-1345

# Characterizing Seismic Activity in the Carpathian Foreland: Insights from Tectonic and Anthropogenic Sources Using Advanced Learning techniques and Seismic Monitoring

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Seismic activity in the Carpathian's foreland is shaped by a complex interplay of natural tectonic activity and anthropogenic processes. The region's seismicity arises from both complex fault systems driven by various tectonic processes and human-induced events, such as mining, oil and gas extraction, and infrastructure development, which pose significant challenges for seismic monitoring. Recent seismic sequences, including those near the bending of the southwestern Carpathians in 2023, the foreland of the Eastern Carpathians in 2013, and other fractured areas, have highlighted the evolving seismic hazard in these regions.

With the recent expansion of the Romanian seismic network, which now includes nearly 200 broadband and short-period stations continuously recording ground motion across the country, we have access to high-quality data that significantly enhances the resolution of seismic analyses. This expanded network allows us to better characterize seismicity patterns in regions where industrial processes overlap with tectonic activity. Traditional catalog and waveform analyses have faced challenges in clearly distinguishing between tectonic and anthropogenic seismic events. The implementation of advanced learning techniques has greatly improved our ability to separate and classify these events. Our results promise to significantly enhance the Romanian earthquake catalog, providing more precise and detailed data essential for seismic hazard assessment, earthquake risk mitigation, and the development of robust earthquake forecasting models.

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## S08 Recent Advances and Challenges in Environmental Seismology

### AS25-0142

# Application of Rayleigh Wave Ellipticity to Subsurface Gas Transport: Insights from Cumbre Vieja Volcano

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Rayleigh wave ellipticity has proven to be a valuable tool for monitoring near-surface hydrological processes, such as water dynamics and pore pressure variations. However, its potential for tracking subsurface gas transport remains largely unexplored. By leveraging its sensitivity to pressure-driven changes in seismic velocities of permeable materials, this method offers a new perspective for continuously monitoring gas migration.

In this study, we explore the application of Rayleigh wave ellipticity for tracking diffuse degassing processes. As a case study, we analyze data from Cumbre Vieja Volcano, La Palma, identifying spectral signatures associated with pressure-induced gas transport and its modulation by local geological and hydrogeological conditions. Our results reveal a strong correlation between Rayleigh wave ellipticity variations and documented $CO_2$ emission episodes, demonstrating the method's potential for tracking transient subsurface gas flux. These findings suggest that monitoring barometric pumping variations provides a robust approach for assessing gas transport dynamics, even in non-eruptive settings.

The results highlight the sensitivity of Rayleigh wave ellipticity to subsurface gas transport processes, supporting its use as a high-resolution geophysical technique for continuous volcanic monitoring. This method provides valuable constraints on both long-term trends and short-term fluctuations in gas migration, making it particularly relevant for volcanoes with limited direct gas emissions at the surface. Moreover, its effectiveness even during periods of strong tremor makes it a promising complement to conventional volcano monitoring techniques, particularly for detecting pressure-driven gas migration in permeable volcanic deposits.

## AS25-0165

# Near-surface investigation using Seismic method in the Deccan volcanic Province: A critical zone case study

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The critical zone plays a vital role in life on Earth, as it encompasses the interaction among the geosphere (mainly the topmost layer of the Earth), hydrosphere, atmosphere, and biosphere. The critical zone processes significantly impact the evolution of the near subsurface. Therefore, some of these natural phenomena occurring in this zone can be understood by investigating variations in the near subsurface physical properties. This study utilizes the multiple-channel analysis of the surface waves technique to estimate the subsurface shear wave velocity of the top 50 m around Pune city located in the Deccan region. A seismic characterization chart of various basalt units is developed by co-analyzing the shear wave velocity models and field observations. Further, the weathering zone is estimated as the shear wave velocity depends on the strength of the rock. Since the weathering processes respond to water availability and vegetation, these velocity models are further interpreted to understand the water movement pathways and potential water storage zones and how they impact the vegetation pattern in the study area. Finally, we propose hypotheses by connecting these dots and unraveling the process occurring in the critical zone in the study area and potentially in volcanic terrains across the globe.

## AS25-0240

# Seismo-acoustic and GNSS monitoring of a record-breaking storm in the Black Sea: Evidence of climate change and intensifying natural hazards

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In August 2024, a record-breaking storm struck the Black Sea coast of Romania, setting new precipitation records and highlighting the intensifying impacts of extreme weather events. This study combines seismic, acoustic, GNSS, and hydro-meteorological data to provide a comprehensive analysis of the storm's evolution and impacts. High-frequency seismic data (>30 Hz) captured the distinctive signatures of precipitation and wind, while low-frequency seismic data (<1 s) revealed the effects of powerful storm waves. Infrasound observations and satellite data provided insights into lightning activity associated with the storm, while ERA5 reanalysis data offered detailed hourly estimates of precipitation, wind speed, and wave height. Additionally, GNSS-derived integrated water vapor calculated from tropospheric delays allowed us to track atmospheric moisture dynamics. Our analysis shows a strong correlation between these diverse datasets, demonstrating how they can complement traditional meteorological observations, which often lack the spatial and temporal resolution to capture fast-evolving storm systems. For example, satellite sensors may provide information with limited spatial and temporal resolution, leaving critical gaps in storm evolution and monitoring. This study underscores the potential of multidisciplinary approaches to improve our understanding of extreme weather events and their links to climate change, offering valuable tools for better forecasting and risk mitigation in vulnerable regions like the Black Sea.

## AS25-0261

# Geotechnical Assessment and Machine Learning-Based Analysis of Seismic and Rainfall-Induced Landslides in the Indian Himalayas

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Seismic activity and intense rainfall are major triggers of landslides in the Indian Himalayas, posing severe risks to infrastructure and communities. Understanding the complex interaction between seismic forces, slope stability, and environmental factors is crucial for effective hazard assessment and mitigation. This study integrates geotechnical analysis, slope stability modelling, and machine learning techniques to evaluate landslide susceptibility in the region. By analysing key geotechnical parameters—such as soil strength, slope angle, groundwater influence, and seismic loading—this research identifies critical failure zones and assesses stability under varying environmental conditions. Numerical modelling techniques, including limit equilibrium and finite element methods, are employed to simulate slope behaviour and potential failure mechanisms. Additionally, machine learning algorithms are applied to large datasets comprising geological, hydrological, and meteorological variables to enhance landslide prediction accuracy. The integration of data-driven techniques with geotechnical assessments provides a comprehensive approach to understanding landslide triggers and improving risk assessment models. The findings contribute to the development of more effective early warning systems and highlight the importance of interdisciplinary collaboration in environmental seismology and geohazard management.

## AS25-0296

# Coherence-based characterization of long-lasting long-period monochromatic signals

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Continuous seismic data analysis reveals signals associated with physical processes within the Earth or on its surface. At periods longer than 25 s, back-propagation of surface waves recorded by global seismic networks has identified previously unrecognized seismic events that are absent from traditional earthquake catalogs. Previous studies discovered unidentified events, most of which occur in polar regions, along mid-ocean ridges and tectonic boundaries, which could not be linked to known tectonic structures. However, global surface wave-based methods have limited ability to detect long-lasting and monochromatic signals generated by volcanic, environmental, and oceanic processes due to their narrow frequency bands, long duration, and unclear onset. Characterizing such monochromatic signals may provide valuable insights into volcanic activity, ocean waves, and glacier dynamics.

In this study, we apply a coherence-based approach to characterize long-period monochromatic seismic signals. We compute temporal coherence, averaged across all station pairs within a broad-band seismic network in Japan from 2003 to 2022. Our analysis identifies several periods with coherent, long-lasting monochromatic signals. We examine both well-known and previously unreported signals originating from the Gulf of Guinea, Vanuatu, the submarine volcano, and the Canadian Arctic Islands. Using inter-station arrival times derived from cross-correlations among global seismic stations, we estimate source locations of these signals. Additionally, we apply the matched-filtering method to identify repeating events. Our findings establish a foundation for systematically detecting and characterizing volcanic and environmental monochromatic signals, which are increasing due to ongoing climate change.

## AS25-0311

# Seismological observations of the large rockfall on Rzenik Mountain (N Slovenia) on 26 February 2021 and its characteristics

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On 26 February 2021 at 05:16 UTC a large rockfall occurred on Rzenik Mountain (1833 m) in the Kamnik Alps. Its 400 m high North wall is composed of Triassic limestone and is known as one of the crumbliest in Slovenian mountains. We describe seismological observations of this rockfall, not triggered by an earthquake, as well as morphometric and other characteristics. The rockfall caused ground motion so strong that it was detected by most of the seismographs of the Slovenian seismological network at distances from 15 to 126 km, and by two seismographs in Austria. There were no eyewitnesses of the rockfall, because it happened in a remote valley in early morning. Therefore, seismographs were the first to detect it, followed by observations of a dust cloud. A comparison of seismograms of this rockfall with seismograms of magnitude 1.8 tectonic earthquake and a large blast in a nearby active quarry, revealed a variety of seismic waves, their generation and frequency content, depending on the nature of the source. This enables quick seismological discrimination of different events. By comparison of ground and aerial images taken before and after the rockfall, we quantitative assessed its extent. The break was 200 m high and 100 m wide, and the volume of the fallen rocks deposited across an area of 13 hectares was estimated on 625,000 $m^3$. Geomorphologic analysis of a high-resolution LiDAR DEM showed that large rockfalls occurred in this area also in the past.

## AS25-0571

# Integrated characterization of mining contamination using geophysical, geospatial and chemical analysis: case study of the São Domingos Mine (Portugal)

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This work presents an environmental management model for the risk assessment of mining soils contaminated by heavy metals (HMs) in the São Domingos Mine (Portugal), combining geophysical, chemical and hyperspectral datasets.

Geophysical and geospatial methods allow us to determine their depth and the volume of accumulated materials in mining areas. The Multispectral Imagery (MSI) onboard Sentinel-2 offers significant advantages, including high spatial resolution, open access for quick data download, and frequent revisitation of the study area. Hyperspectral imagery (HSI) provides a more detailed spectral characterization of surface materials, enabling precise identification of contamination signatures.

We intend to identify areas with fully exposed soil using spectral indices, which combining spectral measurements at different wavelengths can improve classification accuracy. Contaminated soils usually exhibit discrepancies in optical properties that can be detected in the visible region bands of the MSI and HSI datasets. All the datasets can be integrated into Artificial Intelligence algorithms, that allows the generation of risk maps (high levels of contamination). This model allows the optimization of the sampling and chemical analysis phases. In addition, it can provide important real-time information for decision-making related to pollution monitoring and management.

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## AS25-0722

# Using Seismometers to Monitor Storms: A Case Study from the Western Black Sea, Türkiye

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Seismometers, originally designed to detect earthquakes, also offer valuable insights into environmental changes, particularly in regions with sparse meteorological stations. These instruments continuously record ambient seismic noise, which is influenced by both human activity and atmospheric disturbances. As a result, variations in ambient seismic noise levels can reflect changes in meteorological conditions at local and synoptic scales. In this study, stormy days and high wind speed events (>17.2 m/s) were identified using hourly wind direction and speed data recorded between 2014 and 2023 at three collocated seismic and meteorological stations along the Western Black Sea coast. The impact of meteorological conditions on seismic noise was analyzed across a broad frequency range using power spectral densities and spectrograms. The findings of this study highlight the extent to which high-speed winds influence seismic ambient noise at various locations, highlighting the potential of seismometers as a complementary tool for environmental monitoring.

## AS25-0733

# Shear-wave velocity structure of the Chinshan coastal plain in northern Taiwan

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The Chinshan plain, located on the north coast of Taiwan, is a half-graben basin because of the sinking of the Chinshan fault and the Shanchiao fault. According to a geological drilling and seismic survey, the deepest bedrock near the Sanchiao fault is more than 550 meters deep. However, the structures of the Chinshan plain and the faults are still unclear because of the deep alluvium covering the plain. In this study, we conducted the microtremor survey, including dense single-station measurements for horizontal-to-vertical spectral ratios (HVSR) and three array measurements for F-K spectrum analysis, to investigate the seismic site-effect and shear-wave velocity (Vs) structure of the Chinshan plain. The mHVSRs in most of the region at the center of the plain present significant amplification, with the predominant frequencies between 1 Hz and 2 Hz. The significant site amplification is controlled by the soft alluvium and weathering soil near the ground surface, and disappears in the region close to the basin border. The thickness of the alluvium, with Vs lower than 0.6 km/sec, varies between tens of meters and two hundred meters. The Vs of the layer beneath the alluvium is between 1.0 km/sec and 1.5 km/sec, and should be the redeposited pyroclastic tephra from the Tatun Volcano. Finally, although the pre-Tertiary bedrock of the Chinshan plain is also roughly described, our survey is still insufficient to detect the structure of the Shanchiao fault with a deep dipping angle.

## AS25-0767

# The seiche that shook the Earth for 9 days: the September 2023 tsunamigenic landslide in Greenland

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Climate change is increasingly predisposing polar regions to large landslides. Tsunamigenic landslides have occurred recently in Greenland (*Kalaallit Nunaat*), but none have been reported from the eastern fjords. In September 2023, we detected the start of a 9-day-long, global 10.88-millihertz (92-second) monochromatic very-long-period (VLP) seismic signal, originating from East Greenland. In this study, we demonstrate how this event started with a glacial thinning–induced rock-ice avalanche of 25 × 106 cubic meters plunging into Dickson Fjord, triggering a 200-meter-high tsunami. Simulations show that the tsunami stabilized into a 7-meter-high long-duration seiche with a frequency (11.45 millihertz) and slow amplitude decay that were nearly identical to the seismic signal. An oscillating, fjord-transverse single force with a maximum amplitude of 5 × 1011 newtons reproduced the seismic amplitudes and their radiation pattern relative to the fjord, demonstrating how a seiche directly caused the 9-day-long seismic signal. Since the original publication of our results, other groups analysed satellite altimetry data captured by NASA's Surface Water and Ocean Topography (SWOT) mission that directly confirms a slowly dissipating, >9-day long, initially 8 m-high seiche. Our findings highlight how climate change is causing cascading, hazardous feedbacks between the cryosphere, hydrosphere, and lithosphere.

## AS25-0793

# Exploring fracture networks beneath the Hengill Geothermal Field (Iceland) through probabilisitic anisotropic P-wave tomography

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Mapping of fracture networks is critical to the exploration and responsible exploitation of geothermal resources. Fractures provide the permeable pathways required for efficient heat extraction and knowledge of their subsurface distribution is necessary for optimal well placement and reservoir modelling. Additionally, fractures play a significant role in induced seismic hazards both by decreasing rock strength and by providing hydraulic connections between fluid injection/extraction sites and surrounding fault networks that may slip in response to pore pressure perturbations. However, constraining fracture distributions in 3D can be challenging. Geologic mapping provides limited information regarding how these systems evolve with depth while exploratory drilling is expensive and only provides point-wise constraints that may not reflect larger-scale structure. Seismic imaging utilising local earthquakes provides a cost-effective means to overcome these issues and map fractures at the reservoir scale. In this contribution, we constrain the anisotropic P-wave velocity structure of the Hengill Geothermal Field (Iceland) using arrival times from natural and induced seismicity. A Bayesian Monte Carlo sampling approach is used to construct likely velocity models and posterior parameter distributions from which we evaluate hypotheses for fracture properties. The imaged slow P-wave propagation directions constrain the average fracture plane orientations while the degree of alignment and extent of fracturing is inferred from the strength of velocity anisotropy. Preliminary results reveal spatially variable patterns in these fracture properties. We explore possible mechanisms behind this heterogeneity (e.g. deformation related to topographic loading, tectonic and magmatic stresses, and geothermal energy production) and its relationship to local seismicity patterns.

## AS25-0813

# Using ambient seismic noise to study sedimentary aquifers: the SIAS project

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The Seismic Imaging for Aquifers in Sediments (SIAS) project explores the use of ambient seismic noise to monitor groundwater variations in sedimentary aquifers of the Pampean region, in the northeast of Buenos Aires Province, Argentina (La Plata). Groundwater characterization in these extensive aquifers is often challenging due to subsurface heterogeneity and limited direct observations. Seismic ambient noise analysis offers a non-invasive yet underexplored approach to assessing subsurface properties. The Horizontal-to-Vertical Spectral Ratio (HVSR) method is widely used to estimate site resonance frequencies, and its application in geology has expanded to sediment thickness estimation. However, its use in groundwater studies remains largely underexplored, despite its promising potential.

This study integrates data from a permanent seismic station and a temporary seismograph network to assess seasonal and long-term changes in aquifer conditions. The objective is to evaluate how ambient seismic noise can provide indirect information about groundwater, particularly in regions with limited hydrogeological monitoring infrastructure. The project involves a collaboration between experts in seismology, geology, and hydrogeology to explore the potential of HVSR in groundwater monitoring. This approach aims to enhance hydrogeophysical techniques and contribute to the development of cost-effective methods for aquifer characterization and long-term groundwater assessment.

## AS25-0822

# Tracking Seismic Signatures of Storm Vaia (2018) with the SWATH-D Seismic Array

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The climate system is a vast, ever-evolving network shaped by nonlinear interactions and feedback loops that create a constantly shifting and unpredictable environment. Detecting and tracking abrupt changes within this dynamic system is a major challenge, compounded by delayed responses and the critical need for precise, real-time data to distinguish sudden shifts from natural variability. However, recent breakthroughs highlight the potential of dense seismic networks, which provide a unique lens into climate system dynamics, particularly in capturing transient atmospheric-seismic interactions and identifying abrupt climate shifts via seismic proxies. These networks offer a powerful new perspective to reveal the fundamental dynamics driving the climate system's evolution at the mesoscale and synoptic scales. To unlock this potential, we leverage the unprecedented opportunity provided by the SWATH-D seismic array to analyze the dynamic response of Storm Vaia (2018). Using the Hurst exponent, a critical metric for assessing spatiotemporal persistence, we apply two-dimensional detrended fluctuation analysis (TD-DFA) to detect subtle, abrupt shifts within a coupled spatiotemporal framework. Our findings demonstrate that by continuously monitoring fluctuations in fractal properties, TD-DFA uncovers hidden transitions in system dynamics, offering a robust method for identifying rapid changes in climate-related processes. This study highlights the transformative potential of seismic networks, analyzed through fractal techniques, to enhance our ability to detect and understand sudden environmental changes, revealing new insights into the evolving behavior of the climate system.

## AS25-0942

# Microseismic monitoring of the Quest CCS site, Alberta, Canada using multi-technology sensors

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CCS is one solution to reducing the amount of $CO_2$ in the atmosphere. Microseismic monitoring represents a key surveillance technology to verify the integrity of large-scale $CO_2$ storages, since the interpretation of microseismic events may provide insight into $CO_2$ migration within the storage reservoir and potential caprock failure. The Quest CCS site in Alberta, Canada, aims to store 27 million tonnes of $CO_2$ within its storage complex from its start-up in 2015 until 2040. Microseismic monitoring is part of the MMV plan. A string of eight 3-component geophones installed in a deep monitoring well confirmed that the Area of Review (AOR) with a 10 km radius around Quest was seismically quiet before injection operations started. With continued injection over time, low levels of low-magnitude seismicity were observed within the AOR. In addition, 153 surface nodes arranged in groups were temporarily deployed. A DAS cable installed in one of the injection wells was interrogated for a period of six months.

More than 600 microseismic events of magnitude ranging from -2 to 0.8 were detected and located within the AOR over the time period evaluated. All events were located in the Precambrian basement below the reservoir, posing no risk to containment. This rich dataset allows for the comparison of different monitoring technologies both in terms of detectability and locatability of events. We demonstrate how signal and array processing techniques can significantly lower the event detection threshold. Event location uncertainties can be reduced by combining downhole geophone, surface node and downhole DAS data.

## AS25-0949

# Tracking subsurface dynamics on El Hierro and La Palma: Temporal variations in seismic anisotropy during volcanic unrest

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Active hotspot volcanism reflects subsurface magma processes that reshape stress patterns and seismic anisotropy. Deeper insight into these patterns enhances models predicting eruption likelihood and prolonged seismicity. To capture significant variations across small spatial and temporal scales, detailed studies are required. Here, we investigate seismic anisotropy before, during, and after volcanic eruptions. We use local seismicity around El Hierro and La Palma, the two westernmost islands in the Canaries and sites of the most recent volcanic eruptions in the archipelago. We obtained 215 results in El Hierro during and after the 2011/2012 eruption and 908 results around the 2021 eruption in La Palma using five and two three-component broadband seismic stations. On La Palma, most seismicity and splitting results were recorded during the eruption and the island's simultaneous deflation. While seismicity locations do not change significantly, and the fast shear wave polarisation direction remains mostly constant, some variations can be linked to changes in the magmatic plumbing system. On El Hierro, the radial pattern reflects stresses from island uplift during magma intrusions. Temporal subsets show variations in event location, depth, and fast polarisation direction due to ongoing changes in under- and overpressurisation. Starting in 2018, results suggest renewed subsurface activity in deeper plumbing, influencing seismicity rates but not vertical island movement.

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## AS25-1015

# Insights into the fluid migration dynamics of the La Palma eruption from ambient seismic noise

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Ambient noise correlation analysis is widely used to monitor temporal changes in the medium, typically associated with variations in the stress field and/or fluid movement. In this study, we investigate the 2021 eruption of La Palma, to assess its structural effects during the post-eruptive stage. With this study, we aim to localize medium changes to constrain the depth of the most affected structures and propose possible mechanisms responsible for these alterations.

Auto- and cross-correlation functions were computed using the phase cross-correlation method and linearly stacked with a 3-day sliding window, a combination that yielded the best results. The analysis of 3 years of data revealed occasional decorrelation before the eruption, followed by a well-defined decoherence period after the eruption. Furthermore, examining the relationship between waveform correlation and lag time—using autocorrelations from pre- and post-eruptive periods—enabled us to identify phase shifts and waveform distortion, both of which are sensitive to different parameters and crucial for inferring possible underlying mechanisms. Phase shifts indicate velocity changes without structural modifications, whereas waveform distortion suggests geological alterations.

Additionally, we inferred the depths at which the most significant medium changes occurred. Our findings indicate that decorrelation is observed at lag times corresponding to changes at depth, while the surface structure remained relatively unaffected at depths up to approximately 8 km, both before and after the eruption.

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## AS25-1066

# Ambient seismic noise levels in the northern region of Évora, Portugal

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Understanding the origin of background seismic noise at a particular site and being able to quantify it can provide valuable information to enhance the performance of a seismographic network.

The main goal of this work is to analyze the background noise levels recorded from a temporary seismic network composed of 12 broadband digital stations (CMG-3ESP 60s), deployed between 2011 and 2012 in the seismically active zone of Arraiolos (northern region of Évora). To analyze the noise spectrum of each station of this seismic network, we used a MATLAB-based spectral analysis method, capable of examining the noise level at various frequencies, times of the day or periods of the year. The noise spectra were systematically calculated in all frequency bands and compared with global noise limits.

We intend to acquire an understanding of the probabilities of power spectral density for each seismic station deployed in the study area, in particular of the temporal and seasonal variability of noise and its sources. Additionally, this research assists in gaining a clearer understanding of the effects of local atmospheric, geological, topographic, and human activities on the levels and variations of background seismic noise in the Arraiolos Seismic Zone.

This study provides valuable insights for the implementation and optimization of future experiments in this region.

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## AS25-1108

# Seismic noise interferometry in sustainable resource management

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Seismic noise interferometry has become a powerful tool for imaging and monitoring the subsurface, offering significant potential in environmental seismology. This technique offers valuable insights into structural dynamics and stress field variations, which are important for ensuring subsurface stability, improving natural hazard assessments, and optimizing resource management.

In this presentation, we explore its use in two sectors that are important in the transition to sustainable energy: shallow geothermal energy and mineral resources. Shallow geothermal energy is gaining relevance as a clean energy source, requiring improved monitoring techniques for efficient and safe development. At the same time, minerals like copper play a key role in renewable energy technologies, including electric vehicles and power grids. However, increased production leads to a rise in tailings, which are stored in dams. Monitoring these tailings dams is essential for ensuring structural stability and preventing environmental hazards. However, in active resource-related sites, coherent but variable seismic noise sources create challenges for effective subsurface monitoring.

We demonstrate how seismic noise interferometry can provide valuable insights into subsurface dynamics and highlight its potential for improving resource management in diverse geological settings.

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## AS25-1175

# Investigating temporal changes in the subsurface structure of São Jorge Island during the 2022 seismic crisis through ambient noise interferometry

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In March 2022, a seismic crisis began on São Jorge Island, which was quiescent since a volcanic eruption-related crisis in 1964. From March until the end of 2022, over 12,000 earthquakes up to ML 3.8 were recorded. Seismicity and geodetic modelling suggested a magmatic intrusion, resulting in gas release, fluid circulation, and pressure changes within the subsurface volcanic system, which often cause variations in the seismic structure.

To investigate eventual spatial-temporal variations in the seismic structure, we analysed continuously recorded data from January 21 to December 22 from two permanent stations (PMAN and ROSA) operated by the Instituto Português do Mar e da Atmosfera. The data were divided into one-hour files and filtered between 1–3 Hz for autocorrelation and 0.1–1.0 Hz for cross-correlation. The Phase Auto- and Cross-Correlation method was used, with functions stacked over three days to ensure a stable noise response. We calculated waveform similarity and relative velocity changes, comparing these with rainfall data and GPS-derived ground deformation.

The two stations exhibited varying results. PMAN, closer to the island center, showed a slight recovery in waveform similarity at shallower depths during the summer of 2022, followed by a decline in Autumn. PMAN data reflected more systematic decorrelation when the crisis began, likely due to disturbances in the seismic structure between 8–10 km and deeper than 15 km.

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## AS25-1252

# Using microseism to study Earth's ocean environment

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Interactions between ocean waves traveling in opposite directions generate seismic waves with periods between 3 and 10 s, known as secondary microseisms (SMs), which have been observed worldwide. The amplitude of SMs is influenced by ocean bottom sediments and ocean activity near shorelines. We introduce how the sediments modulate the amplitudes, and we demonstrate that incorporating the modulation effects into SM modelling improves the agreement between the synthetic and observed SM energy. Additionally, we discuss how sea ice affects ocean wave reflections near the shorelines of Antarctica.

## AS25-1286

# Ocean-floor seismic observatory: leveraging Distributed Acoustic Sensing on underwater cables—A case study in central Chile

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Distributed acoustic sensing (DAS) transforms fiber-optic cables into extensive and dense seismic networks. Although less sensitive to ground motion compared to traditional networks, they offer new possibilities, especially in harsh locations such as the ocean seafloor. These networks are valuable for both classical seismology and understanding the interaction between the ocean and the solid Earth

Since October 2023, the ABYSS ERC project has implemented an observatory composed of three Distributed Acoustic Sensing (DAS) instruments that continuously record data from fibers spanning 450 km along the Chilean coast. This project addresses challenges in data processing, management, and sharing. With the system now operational, we have a wealth of information related to the environment.

Despite higher noise levels and uneven ground coupling, the cables can record microseismic noise, offering high-resolution images of shallow crustal structures. In combination with coda waves and P to S converted phases at the interface between the sediment and the bedrock, shallower structural variations can be observed. Recently, we identified strong impedance contrast structures, such as faults, based on laterally reflected surface waves. This approach opens up new horizons for structural imaging and monitoring.

Continuous monitoring of microseismic noise and ocean gravity waves offers insights into ocean-solid Earth interactions, including the generation of microseismic noise through coastal reflections.

Finally, the project also explores acoustic signals from local ships to characterize the cables further. This innovative use of DAS on underwater cables opens new horizons for seismology and environmental monitoring in coastal regions.

## AS25-1310

# Using onshore arrays for cost-effective monitoring of offshore CO2 storage sites in the Southern North Sea

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To meet 2050 emissions reductions targets, dozens of offshore geological $CO_2$ storage projects are being developed across the UK continental shelf, many of which are in the Southern North Sea. Microseismic monitoring is an important component for the planning and operation of geological $CO_2$ storage projects. Microseismicity can provide insights into fault density and faulting style, overburden fracturing, and the state of stress around a storage complex. Understanding background seismicity is key to discriminating and determining the risk of induced seismicity that could result from injection and can help manage public perception of projects. In the Southern North Sea region, the UK national seismic network has a detection capability of approximately $M_L$ 1.5, and epicentral location uncertainties on the order of several kilometres. In its current form, it is likely insufficient for risk-based monitoring approaches.

One potential solution is to augment the UK network with onshore seismic arrays. In October 2023, we deployed a temporary dense array consisting of eight three-component broadband sensors on the North York Moors, Yorkshire, UK. By calibrating detections from f-k beamforming against data from the British Geological Survey earthquake catalogue and using noise statistics, we estimate this deployment improves detection capability to ca. $M_L$ 1.3, which could improve to at least $M_L$ 1.0 for a permanent deployment. Furthermore, the backazimuthal information from seismic beamforming can also improve location accuracy in the region. This deployment shows that onshore dense arrays can offer cost-effective, real-time microseismic monitoring of $CO_2$ storage projects in the Southern North Sea.

## AS25-1366

# Evaluating earthquake triggering potential for landslides in Norway using remote sensing and seismological data

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The significant hazard posed by landslides in Norway has prompted our research into their triggering mechanisms. When considering landslide triggers in Norway, the predominant ones are precipitation and snowmelt. Nevertheless, recent research expanded the understanding of landslide triggers in Norway, providing evidence of historical earthquake-induced landslides (EQIL). This study aims to further investigate earthquakes' potential to trigger landslides in Norway. We do this by investigating the spatial and temporal distributions of landslides in Vestland, which is one of the most landslide-prone regions in Norway. For this region, we study the landslides that were reported in the national landslide inventory that has been developed and managed by the Norwegian Water Resources and Energy Directorate (NVE). We supplement this with landslide events extracted from optical satellite data. For the region of interest, we analyze the key conditioning factors (lithology, slope angle and land cover) and correlate these to the precipitation data. This way we exclude landslides triggered by rainfall. Additionally, to define the precise timing of landslide events and verify their connection to seismic activity, we use the database of the Norwegian National Seismic Network (NNSN) to identify seismic recordings of earthquakes and landslides from the nearest seismic stations. This allows us to precisely pinpoint the timing of landslides detected via optical satellite imagery, overcoming challenges such as cloud coverage and limited temporal resolution. We can thus determine various landslide-triggering mechanisms in Vestland, such as precipitation versus earthquakes, which improves the understanding of the dynamics of earthquake-related events in Norway.

## S09 Cryoseismology

### AS25-0022

# Cryoseismology studies for monitoring surface environment in polar regions: A decade progress around the Dronning Maud Land, East Antarctica

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Majority areas of Antarctica and Greenland are covered by the thick ice sheet and characterized by evolving cryosphere surroundings. In polar regions, associated with recent trend on climate change such as global warming, glacier relating earthquakes are increasing during 21st century. In this presentation, a decade of progress in "Cryoseismology" in East Antarctica, particularly in the Dronning Maud Land, is reviewed by focusing on major scientific achievements from seismic and infrasound investigations. For exmaple, specific cryoseismic events are demonstrated, which occurred in the coastal area of the Lützow-Holm Bay (LHB). Frequency-overtone signals in harmonic seismic tremors were recorded by assuming constant-durating sources, suggesting inter-glacial asperities that generate characteristic tremors. Moreover, the tremor events in April 2015 were identified to be associated with the discharge of large volume of sea-ice, together with collision between icebergs which drifted from eastward offshore of the Enderby Land (Tanaka et al., Polar Science, 2019). Moreover, infrasound generating sources' locations and propagation directions were determined by using array deployment. Time-space variations of the infrasound source locations in 2019–2021 were studied by a combination of two local arrays, deployed at two coastal outcrops of LHB. Temporal (seasonal) variations were clearly identified in frequency contents of the signals as well as propagating directions during the years (Kanao et al., Annals Geophys., 2024). These scientific findings and related instrumental technology could give rise to new insights into the understanding of inter-relating dynamics between cryosphere, atmoephere, ocean and solid earth in polar regions.

## AS25-0320

# Cryoseismic monitoring in the Schirmacher Oasis, East Antarctica, using single station

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We conducted a two-month-long cryoseismic monitoring study in the Schirmacher Oasis, East Antarctica, to investigate icequake activity caused by the movement and melting of ice sheets. For this purpose, we deployed a RaspberryShake (RS) seismometer on Antarctic land for one month and on the ice for another month. Through a comparative analysis of the recorded seismic data, we gained insights into ice dynamics and diurnal icequake patterns. The RS instrumentation, powered by solar energy, offers a cost-effective approach for establishing a dense seismic network. During installation, the RS, solar controller, and Li-ion battery were housed in a wooden box lined with nitrile foam for insulation. Our comparative analysis revealed that icequake activity followed a distinct diurnal pattern, with more events occurring during the daytime. We employed a standard STA/LTA trigger for event detection and correlated the results with data from the All Weather Station (AWS). Additionally, we identified seismic signals indicative of shallow and deep icequakes. During deployment over the ice, we observed unusual recurrent long-period step-response signals on the horizontal component, which we interpret as potential RF interference, instrumental error, or a rapid and permanent tilt. As a pilot project, these findings highlight the need for a denser seismic network and more detailed investigations to further understand the impact of climate change on melting ice sheets.

## AS25-0486

# Glacier process discovery and change monitoring of ice sheet outlet glacier systems: cryoseismology in the East Antarctic context

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Glacier investigations that make use of seismic signals together with the extensive toolbox of seismology have become more widespread in recent years. Such investigations span studies of mountain glaciers in great detail through to reconnaissance investigations of ice streams, or other extensive areas in the polar regions. This contribution focusses on the latter cases, where seismology offers a means of knowledge generation in remote locations on a large scale: the current context for cryoseismology in East Antarctica.

We report on recent developments in computational techniques for seismic signals recorded in the noisy Antarctic environment, where it is often necessary to handle Southern Ocean, adjacent ice shelf signals and local glacier seismicity occurring in the same time window. We also share information on recent field deployments, developed in tandem with the computational methods, in the Lambert, Denman-Scott and Vanderford-Totten Glacier systems.

Using legacy and newly collected data we show that both diurnal and tidal influences contribute to the seismic wavefield in various locations, and compare the impacts of constant small glacier events with intermittent large events. Monitoring major outlet glaciers of the East Antarctic Ice Sheet by seismic means is emerging as a significant capability area through combining semi-automated data analysis workflows with a bold program of field deployments.

## AS25-0574

# Spatio-temporal analysis of iceberg calving events in Greenland from 2013 to 2024

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The Greenland Ice Sheet is a major contributor to global sea-level rise, with iceberg calving events playing a significant role in its mass loss. Identifying and analyzing these events in terms of their spatio-temporal distribution and estimating the associated mass loss are crucial steps in advancing our understanding of the impacts of climate change.

During an iceberg calving event, the detaching and rotating iceberg exerts a time-varying force on the marine-terminating glacier terminus. This force generates seismic signals known as glacial earthquakes, which can be detected by broadband seismic stations located tens of kilometers from the source. To detect and classify glacial earthquakes systematically, we employ a two-step methodology. First, we use a detection algorithm based on the Short-Term Average over Long-Term Average (STA/LTA) method to identify potential calving events. In a subsequent step, we apply a supervised machine learning classifier (Random Forest) to differentiate between glacial earthquakes and tectonic seismic events. The detected glacial earthquakes are then located using a non-linear location algorithm (NonLinLoc). Applying this approach to continuous seismic data from 2013 to 2024, we identify 6’263 glacial earthquakes along the coast of Greenland, predominantly clustered around the largest marine-terminating glaciers, with a distinct seasonal variability observed, peaking in July.

We will present the spatio-temporal distribution of these events, along with their variations in magnitude and their correlation with environmental data. These findings improve our understanding of how calving affects mass loss from the Greenland Ice Sheet and help refine models predicting its impact on future sea-level rise.

## AS25-0650

# Application of horizontal-to-vertical spectral ratio (HVSR) technique for ice thickness estimation on Snow Island, Antarctica

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Snow Island is one of the South Shetland Islands, Antarctica. It is almost completely covered by ice. In January 2025 two seismic experiments were conducted on the island. A temporary broad band seismic station was installed for a month on Hall Peninsula and several hours of seismic recording on the nearest glacier were made. Glacier thickness and structure were also investigated using ground penetrating radar (GPR) with central frequency of 25 MHz along eight profiles. The point of seismic recording lies in the middle of one of the GPR profiles. HVSR technique was applied to the data. The estimated resonance frequency is 12 Hz and the estimated ice thickness is about 40 m which corresponds well with the thickness obtained from GPR measurements.

## AS25-0764

# Potentials and challenges of environmental seismology with distributed acoustic sensing in the high Arctic

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The Arctic is warming nearly four times faster than the global average, leading to significant changes in glaciers, permafrost, and the stability of polar landscapes. Understanding these dynamic processes is crucial for assessing climate-driven hazards and long-term environmental changes. Distributed Acoustic Sensing (DAS) is a modern measurement technology that enables time-lapse data acquisition with unprecedented sensor density and spatial sampling down to the metre scale. This study explores the advantages of DAS over traditional geophones for monitoring glacier and permafrost dynamics.

We conducted a multi-season experiment in Hornsund, SW Svalbard, deploying 9 km of fibre across frozen ground and Hansbreen glacier. This represents the first land DAS study conducted in Svalbard. The fibre-optic cable was installed alongside conventional geophones and the permanent seismic HSPA array to evaluate DAS's performance in detecting seismic signals related to ice and permafrost processes. Our analysis compares waveform characteristics, noise levels, seismic velocity variations from noise interferometry, event detectability, and location accuracy identifying key advantages and limitations of DAS in harsh Arctic conditions.

We showcase seismic events captured during the experiment, including dynamic ice movements and permafrost-related processes, demonstrating DAS's potential for long-term cryoseismological monitoring. Additionally, we discuss best practices for deploying DAS in polar environments and address key challenges such as coupling conditions and fibre maintenance. Our findings highlight DAS's capability to enhance high-resolution environmental seismology in the Arctic while emphasizing the need for further optimization in extreme conditions.

## AS25-0790

# Tracking the sub-glacial river of Glacier d'Otemma with seismic nodes and Distributed Acoustic Sensing

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Alpine glaciers are highly sensitive to global climate change, notably to increasing temperatures. The resulting glacial surface melt diverts into englacial conduits and then to the subglacial drainage system, controlling basal motion and thus large-scale ice flow. Our understanding of the structure and dynamics of the subglacial system is still incomplete, despite its importance for glacier dynamics, sediment transport and subglacial erosion.

In this study, we use seismology to investigate the location, spatial distribution, and discharge of the subglacial channel system of Glacier d'Otemma, Switzerland. Seismic surveys overcome the poor direct accessibility of subglacial channels since they can map their location and discharge with high spatial and temporal resolution through the ice. DAS enhances this spatial coverage of the survey area.

We investigate this potential advantage by combining distributed acoustic sensing (DAS) and seismic nodes to precisely locate the subglacial river. Accordingly, we installed a grid of nodes on the glacier surface of Glacier d'Otemma. Simultaneously, we deployed a fiber optic cable crossing the glacier in a shape of multiple triangles to cover all orientations of wave arrival. Two methods, matched-field processing (MFP) and beamforming, are applied on both the DAS data and seismic nodes data sets. The results are density maps of the glacier showing the probability of source locations for frequency bands associated with turbulent flow below the glacier. This seismic activity mapping identifies the spatial dynamics of diurnal discharge cycles, typical for alpine glaciers, and tracks changes in the subglacial channel pattern throughout several weeks.

## AS25-1010

# Plans and Status for the new Seismic and Infrasound Arrays in Dronning Maud Land, Antarctica

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In 2022, the Research Council of Norway granted in context with the infrastructure project TONe the extension of the existing, broadband seismic station to a seismic array and the additional installation of an infrasound array at Troll in Donning Maud Land, Antarctica. The new Seismic Array is planned to become one of the globally important high-quality seismic observatories since it will be installed on bedrock inside the Antarctic continent. We expect more knowledge about the regional seismicity in Dronning Maud Land, movements in the Antarctic ice shield and the ice shelf along the coastline of Dronning Maud Land, as well as a significant contribution to monitoring global seismicity.

The new Infrasound Array will be co-located with the seismic array. The array will use infrasound waves to allow characterization of upper stratosphere, mesosphere and lower thermosphere dynamics, and quantification of vertical coupling between these layers. In addition, the synergy of seismic and infrasonic sensors is expected to facilitate enhanced observation of glacial movements.

The poster will present the actual status of the array plans regarding instrumentation, geometry, location and power supply. The installation is planned for the austral summer season 2025/26 and first data are expected to be recorded in February 2026.

## AS25-1057

# Density inference in glaciated environments using probabilistic surface wave dispersion inversion

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Ice sheet mass balance is a major component of climate change. To accurately calculate mass balance, however, detailed ice sheet density profiles are required. Snow and firn cores are often logistically expensive or impractical to obtain. Seismic measurements, combined with empirical P and S wave velocity to density relations, are a suitable alternative which have been used to approximate density profiles. The underlying scaling laws, however, are imprecise and uncertain outside the regions for which they were derived.

Here, we instead infer density directly from seismic surface wave measurements, without invoking intermediate empirical relations. Because the sensitivity of these measurements to density is relatively low, quantifying the uncertainty of density estimates is essential. To this end, we invert surface wave dispersion curves using the Hamiltonian Monte Carlo sampling algorithm, which produces a Bayesian estimate of the probability distribution for density.

We apply this approach to create probabilistic density profiles for two regions of interest: a site on the North-East Greenland Ice Stream, and another on the Vatnajökull ice cap in Iceland. At each site, we use novel seismic sources recorded on fiber-optic cables using distributed acoustic sensing.

From the probabilistic density profiles, we infer two key findings: first, that actual density profiles differ significantly from those obtained by scaling relations, and second, that uncertainties of the scaling relations are consistently underestimated.

This study highlights the potential to extract density information directly from seismic measurements using probabilistic approaches and shows that empirical scaling laws may have significant biases.

## AS25-1087

# Seismic monitoring of the Satopanth Himalayan Glacier: investigating icequake signatures and environmental influences

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Understanding glacier dynamics is crucial for assessing ice movement and associated seismic activity. In this study, we installed 15 geophones in the Satopanth Himalayan Glacier to record continuous seismic waveforms at 250 Hz which is down-sampled to 25 Hz from September 19, 2024, to October 7, 2024. The data was analyzed using helicorder plots and spectrograms to investigate the icequake signatures. Our primary concern is to identify the events showing the signatures of shallow icequakes, intermediate icequakes, and deep icequakes. The impact of environmental factors such as solar radiation, wind speed, etc. on the diurnal variations of waveforms. We observed an intriguing signature on station 5 at a frequency of around 8–9 Hz which persisted throughout the whole time of recording, by preliminary observation, we eliminated the possibility of instrumental error so it will be interesting to see what is the reason behind it. We employed PhaseNet, a deep neural network-based arrival time picker trained on the dataset provided by the analyst labeled P and S arrival times from the Northern California Earthquake Data Centre to detect icequake events systematically. Once detected, further study will delve into the location of the detected events by using Partial Waveform Stacking and backtracing the energy.

## AS25-0138

# Isotropic and CLVD Contributions in the Full Moment Tensor of the 2024–25 Ethiopian Swarm, in the East African Rift System

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The East African Rift System (EARS) is one of the most prominent active continental rift zones, extending from the Afar region in the north to Mozambique in the south. It is characterized by extensional tectonics, widespread volcanic activity, and significant seismicity. A prolonged earthquake swarm began on September 27, 2024, in Ethiopia, within the Main Ethiopian Rift, reaching its maximum magnitude with a Mw 5.9 earthquake on February 14, 2025, before ending on February 27, 2025. In total, 313 earthquakes with magnitudes ≥ 4.0 were reported by ANSS ComCat, indicating sustained seismic activity. By applying machine learning techniques to continuous seismic records from nearby stations, we detected several thousand additional events. Relocating and temporal evolution of the cluster revealed multiple distinct phases. Teleseismic body wave and regional surface wave inversions of larger events indicate that most focal mechanisms exhibit normal faulting, consistent with the extensional tectonic regime of the rift. Full moment tensor analysis of all events further reveals a positive isotropic component and compensated linear vector dipole (CLVD) component, likely linked to the dyking process. The largest event, the Mw 5.9 earthquake on February 14, differs from the rest of the swarm in its source mechanism, exhibiting a different double-couple strike, a significant non-double-couple component, and deeper focal depth. These distinctions suggest a more complex source process, possibly related to magma reservoir dynamics beneath Fentale Mountain. This seismic swarm provides unique insights into the interplay between tectonic and magmatic activity in the mature Ethiopian rifting system.

## S10 Volcano seismology

### AS25-0147

# Seismological analysis of the 2024–2025 Fentale-Dofan, Ethiopia, magma driven seismic unrest

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An intense seismic swarm occurred in Ethiopia, starting on December 19, 2024, peaking in a Mw 5.9 magnitude earthquake on February 14, 2025. InSAR analysis shows that a dyke and faulting started from Fentale volcano and reached Dofen volcano between 19 December 2024 to early January 2025. The dyking was accompanied by deflation of a reservoir under Fentale as far as February 14, 2025 when deflation paused and faulting across the Fentale caldera occurred. We combine seismological analyses, such as single station detection, moment tensor inversion, array-based depth determination and waveform similarity clustering to model the seismicity accompanying the intrusion episode and unravel its different stages. We identify three major phases. First, seismicity migrated NE in response to the progressive intrusion of a magma dike from a magmatic reservoir close to Fentale volcano towards Dofen volcano. In this phase, shallow normal faulting earthquakes align above the magma dike over ~50 km length, while sparse strike-slip events toward NE are probably triggered on neighboring faults ahead of the dike's tip, in response to the dike-induced stress perturbation. The second phase corresponds to the local destabilization of the reservoirs' overburden, following its deflation at Fentale and dike feeding between Fentale and Dofen. Finally, a complex rupture accompanied the deep collapse of the reservoir, marked by the Mw 5.9 earthquake, whose moment tensor shows a large non-double-couple component. Our interpretation of seismological results and the identification of the different unrest phases are supported by the independent analysis and modeling of the surface deformation.

## AS25-0173

# The interplay of volcanism and tectonics in the southern Aeolian islands (Tyrrhenian Sea, Italy)

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In the Fall 2023 a nodal array of 120 sensors was deployed to investigate the relationship between seismic and volcanic activity in the southernmost islands of the Tyrrhenian sea. This first seismic deployment provided a unique dataset that allowed us to classify and compare seismic signals revealing differences in time and frequency domain. To complement the 2023 experiment, in 2024 we deployed 16 broadband stations over the southern Aeolian Islands of Alicudi, Filicudi, Salina, Panarea, Lipari and Vulcano, and in the northern Sicilian coast, yielding high-resolution seismic data over a wide frequency range for two years. Data from the permanent stations of the Italian seismic network managed by INGV are merged with the new collected dataset to create a high resolution seismicity catalog that will be then used to image the seismic structure beneath the southern Tyrrhenian sea. Preliminary results from seismological analysis reveal distinct seismic signatures associated with volcanic processes, as also supported by geochemical observations at the surface.

Our study focus on the importance of dense, multiscale seismic networks that contribute to the understanding of the role of tectonics and volcanism in the Tyrrhenian subduction zone. Outcomes from a multidisciplinary approach can advance early warning capabilities in monitoring volcanic regions.

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## AS25-0179

# Imaging Magmatic and Hydrothermal Sources in Central Kamchatka Using Multiscale Seismic Tomography

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Central Kamchatka, a region of intense volcanic and hydrothermal activity, provides an ideal setting for studying magmatic and hydrothermal systems at different depths. We present a review of seismic tomography studies based on data from temporary networks and permanent seismic stations. A multiscale approach, combining ambient noise tomography (ANT) and earthquake tomography (ET), was employed to resolve structures from the upper mantle to near-surface layers. Large-scale structures, including the mantle wedge and crust, were investigated using data from a regional network (2019–2020) and permanent stations. Both ET and ANT revealed low-velocity anomalies in the mantle wedge, coinciding with magma feeding zones of the main volcanic groups. A middle-scale network (2023–2024) provided detailed crustal structures beneath Mutnovsky and Gorely Volcanoes, highlighting deep heat and fluid sources feeding the Mutnovsky Geothermal Power Plant. Local earthquake data (2013–2014) further identified gas- and liquid-saturated zones beneath Gorely Volcano. The Avacha Group of volcanoes was studied using permanent stations and temporary networks (2012–2013, 2018–2019). Beneath Avacha Volcano, tomography revealed a magma reservoir with its top at ~2.5 km depth, potentially suitable for petrothermal energy development. Local-scale passive seismic experiments in hydrothermal discharge zones mapped aquifer layers and impermeable barriers. This multiscale approach offers a comprehensive view of the plumbing systems feeding Central Kamchatka's volcanoes and hydrothermal activity, with implications for geothermal energy exploration and volcanic hazard assessment.

## AS25-0188

# Vulcano Island dynamics through a dense nodal seismic array

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Vulcano Island, the southernmost of the Aeolian volcanic archipelago (Italy), has experienced several unrest episodes, the latest in 2021, increasing significantly the volcanic hazard in the region. Enhancing our understanding of these phenomena requires continuous and dense geophysical monitoring to improve the detection and characterization of unrest signals and to better estimate their spatial extent and temporal evolution.

Although volcano-tectonic and non-volcanic tremors has been identified in this region by the permanent seismic network data, other signals are observed on the continuous waveform data that can be related to the magmatic degassing activity. For a comprehensive understanding of tectonics and volcanism interactions, we deployed a dense array of 40 wireless seismic nodes across the Vulcano island to detect and locate the shallow and low-magnitude seismicity. Continuous seismic signals show different frequency content, variable durations, and occur at different locations. Many of these signals may be linked to the magmatic degassing activity in the vicinity of the La Fossa crater when compared them with other geophysical and geochemical parameters such as gas emissions, vapor output fumaroles. This study presents preliminary findings from the analysis of a one-month dataset of continuous seismic records collected during October-November 2023, compared with a long-term analysis of the local permanent network.

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## AS25-0204

# Scaling laws of spectra of laboratory and volcano-tectonic earthquakes from coda of seismogram

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The physics of small earthquake generation across geological settings remains debated. Given the unobservable in situ conditions and long seismic cycle, laboratory experiments help investigate these earthquake generation processes. Source spectral scaling (corner frequencies, seismic moments) in natural and laboratory experiments can provide insights into common mechanisms. However, observational limitations may pose a serious obstacle to such analyses.

In this study, we compare results of analysis of two datasets. The first is composed of thousands of acoustic emission events ($M \sim -8$) in two rock fracturing experiments (carried out in the RESC of IPE RAS). The second includes ~3500 summital events ($M < 3$) occurring before recurrent eruptions of Piton de la Fournaise volcano, La Réunion, France. We propose a method to estimate spectral source parameters from coda amplitude spectral ratios. Due to its averaging nature, coda waves simplify several requirements of the spectral ratio method, which are difficult to satisfy in these settings.

Source spectrum analyses revealed a high degree of similarity between the fracturing of pre-existing inhomogeneities in rock samples under evenly distributed external pressure and well-studied tectonic earthquakes, exhibiting an inverse cubic scaling between corner frequencies and seismic moments. In contrast, under the loading regime with active formation of new fractures in the laboratory, the observed scaling strongly deviates from cubic scaling. The volcano-tectonic earthquakes caused by pre-eruptive pressurization and occurring along a persisting ring-fault structure also show a cubic scaling between corner frequencies and seismic moments which suggests that they are generated by triggering pre-existing weak fractures.

## AS25-0262

# Characterising the persistent volcanic tremor of the 2021 Cumbre Vieja eruption, La Palma, with fibre-optic seismology

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The 2021 eruption of Tajogaite volcano in the Cumbre Vieja rift zone, La Palma (Canary Islands), was the longest and most destructive eruption on the island in recorded history. During the co- eruptive phase, a distributed acoustic sensing (DAS) interrogator was deployed at the Roque de los Muchachos Observatory to monitor seismic activity. Strain recordings from October 15 to late December captured key features of the background tremor, including its gradual decline after November 2 and its sudden cessation on December 13, marking the end of the eruption. We characterise this tremor through frequency-wavenumber analysis, using a rectilinear 2 km segment of fibre-optic cable to constrain the velocity range of interest. Our results suggest a consistent velocity range confining most tremor activity, and we identify a dominant tremor band between 0.65 and 1.5 Hz. We analyse the temporal evolution of the tremor and attempt to locate its source, exploring migration trends that may provide insights into the eruption's dynamics. Additionally, we identify and filter thermal effects present in the DAS strain recordings to refine the tremor characterisation. Our findings highlight the capability of DAS to characterise volcanic tremor and contribute to the understanding of eruption processes.

## AS25-0297

# Imaging the Valles Caldera volcano using H/V and autocorrelation

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As part of a UTEP/UNM collaboration, we aim to resolve the internal structure of Valles Caldera, one of the quaternary supervolcanoes of North America located near several metropolitan areas, including Albuquerque and Los Alamos, New Mexico. Our study focuses on inferring the current state of the magmatic system beneath the volcano through leveraging scattering properties of the ~80 km caldera system. One-month passive seismic recordings on a line of 97 3-component nodes across the caldera in 2019 are used to study significant near-surface structures related to caldera collapse, backfill, and dome resurgence, and to extricate these features from deeper and more subtle Moho signatures that have been elusive to date. We have utilized a Markov Chain Monte Carlo based inversion scheme to find the best fitting subsurface model to fit the observed horizontal to vertical energy ratio calculated from three components ambient noise data. The shallow structure resolved from the H/V ratio will be jointly inverted with surface wave dispersion curves obtained from ambient noise cross correlation to provide a well resolved structure of the caldera system. Furthermore, autocorrelation functions beneath each station have been calculated to observe the variation along the 1D array. We will be presenting an accurate joint velocity model of the volcano that will address knowledge gaps concerning eruptive potential and the general state of the magmatic system, all of which are currently unconstrained.

## AS25-0318

# Seismic signature of lower crustal sill-type reservoirs beneath the Laacher See volcano, Germany

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The zoned, differentiated upper crustal reservoir that fed the explosive VEI 6 Laacher See volcano (LSV) ~13,000 years ago remained thermally active for over 30,000 years by occasional inflows of fresh basanitic magma from depth. While the magmatic fluid supply channel was discovered in 2013 through persistent deep low-frequency earthquake clusters between 45 and 10 km depth (Hensch et al., 2019), the remaining reservoir structure beneath the LSV was only recently mapped with data from a passive large-N experiment in 2022–2023 (Zhang et al., under review). However, the location, depth and nature of the deeper reservoirs providing inflow are not well constrained.

Recent data from the Eifel large-N network (2022–2023) have provided new insights. Seismic recordings with intermediate station spacing of 2–4 km over 140 km show strong coherent P-to-S converted arrivals from a reflector at ~25.5 km depth over a distance range of about 30 km.. Full waveform modeling of these P25.5s phases suggests a significant reduction in shear wave velocity (<0.5 km/s), accompanied by reductions in P-wave velocity and density. This indicates the presence of a fluid-rich or partially molten sill-type reservoir, as opposed to a solidified crustal layer. We develop a data-driven waveform inversion approach to combine converted phase data from earthquakes at different depths and locations. The results are compared to the clustering of deep, low-frequency earthquakes in the transcrustal feeder channel beneath the LSV.

## AS25-0321

# Stress Variations and Non-Shear Earthquakes Prior to the 2021 Iceland Eruption: Implications for Magmatic Fluid Flow Dynamics

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The 2021 Fagradalsfjall eruption on Iceland's Reykjanes Peninsula followed an intense seismic swarm, providing unique insights into fluid dynamics and seismic behaviour at divergent plate boundaries. Analysing moment tensors of 1,306 pre-eruption earthquakes revealed three faulting regimes: strike-slip, normal, and reverse. Each displayed different stress conditions supported by systematic non-double-couple ISO components indicating significant volumetric changes within the earthquake sources. Normal faulting showed negative ISO suggesting crustal subsidence above the dike, while reverse faulting displayed positive ISO indicating opening due to overpressurized fluids trapped by structural barriers. Slightly positive ISO values of strike-slip events pointed to dike movements. Stress inversion disclosed stable orientation of principal stress axes, consistent with a transtensional setting, yet, highlighted localized stress variations due to dynamic fluid interactions with crustal heterogeneities. The identification of heterogeneous stress within the focal zone combined with volumetric components provides novel perspective on fluid–fault interactions in volcano-tectonic and extensional settings.

## AS25-0381

# Network-based analysis of seismovolcanic signals at Mutnovsky volcano, Kamchatka

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Mutnovsky volcano is one of the most active in Kamchatka, located near the city of Petropavlovsk-Kamchatsky and close to the Mutnovsky Geothermal Plant. Although long-period seismicity has been recorded at the volcano for over 40 years by the Kamchatka Branch of the Geophysical Survey (KB GS) of the Russian Academy of Sciences, detailed studies remain limited due to the lack of dense seismic networks, leaving the sources of seismovolcanic activity poorly understood.

In this study, we applied a network-based method to analyze continuous seismic records from 4 permanent and 21 temporary stations operating in 2023–2024 near Mutnovsky and Gorely volcanoes. We estimated the width of the network covariance matrix eigenvalue distribution. Then, through back-projection of interstation cross-correlations, we evaluated the network response function and located the sources of seismovolcanic signals.

Volcanic tremors within the 1.5–5 Hz frequency range were detected from February 6, 2024, until the end of the monitoring period on March 15, 2024. The tremor sources were located up to 2 km beneath the northeast flank of Mutnovsky volcano, where active thermal springs and fumaroles are located. The observed tremors are likely associated with a hydrothermal explosion at an abandoned well that occurred between February and March 2024.

## AS25-0394

# Capturing variations on depth-dependent elastic properties during the 2020–2021 eruptive episode at La Soufriere, Lesser Antilles

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Seismic tomography is the most important geophysical technique used to provide details of the subsurface in volcanic environments, critical for seismic localization in volcano observatories. Usually the output models consider a static view of the subsurface, although the experiments can record signals in a wide temporal range. Recently, ambient noise tomography (ANT) in different time frames, the estimation of the dv/v parameter (average velocity changes) and time-lapse 3D body-wave tomography studies, provide the temporal resolution needed to capture volcanic processes. Here, we focus on the magmatic system of the La Soufrière volcano in Saint Vincent and the Grenadines, analyzing the 2020–2021 pre-, co- and post-eruptive data. We use a multi-pronged time-lapse approach that features ANT models during the aseismic pre- and post-eruptive phases and body wave tomography during the seismically intense co-eruptive process. Moreover, we produce a b-value profile at depth to evaluate the presence of fluids within the activated faults. The results show the effects of the co-eruptive magmatic intrusion, i.e. a negative velocity anomaly between 2–5 km depth and a positive anomaly at the shallow crust, consistent with the evaporation of the geothermal body. Moreover, from the co-eruptive phase the output models feature a cap-like anomaly consistent with previous geochemical studies and a complex system of reservoirs where fragmentation occurs at different depths, consistent with explosion locations. These results provide important quantification for accepted processes in volcanoes; however, the anomalies do not significantly influence the seismic locations for volcano monitoring purposes.

## AS25-0409

# A Reactivated Swarm Region in Northwest Bohemia/Vogtland: The Role of Fluids

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Earthquake swarms are enigmatic seismic phenomena that occur in a wide variety of tectonic settings, from volcanic to intraplate regions, and are often associated with fluid migration, magmatic activity, or stress redistribution. The Northwestern Bohemia/Vogtland region is a globally recognized hotspot and natural laboratory for such activity. This study first addressed a new earthquake swarm in March 2024 following decades of quiescence near Klingenthal-Kraslice. The structural symmetry and temporal evolution of the swarm indicate the activation of a pre-existing fault by natural hydrofracturing and hydro-shearing under the influence of ascending magmatic fluids.

Seismic modelling shows that the swarm began with a high-pressure intrusion of a CO2-rich fluid, followed by a transition to low-pressure hydro-shearing on the fault, probably associated with CO2-magma mixing. The Vp-Vs ratio in the source volume was greatly reduced during the initial phase of the swarm, and weak earthquakes may have been accompanied by more complex rupture processes than the stronger earthquakes during the hydro-shearing. However, as evidenced by ongoing seismicity reported in the region, our model is currently being reevaluated for its possible use in subsequent swarm sequences. to subsequent swarm sequences. This involves assessing the consistency of high-resolution seismicity patterns and earthquake source mechanisms across different periods of activity.

Our updated analysis gives a broader temporal perspective to reconstruct the spatial and temporal evolution of earthquake swarms in the region. These results provide critical insights into fluid-driven deformation and fault zone dynamics, contributing to a better understanding of geodynamically active regions worldwide.

## AS25-0421

# The relationship between the S wave radial anisotropy in the magma reservoir and the stress field

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Recent studies have reported the existence of the discrepancy between vertically ($V_{SV}$) and horizontally ($V_{SH}$) polarized S-wave velocity structures beneath volcanoes with large calderas such as Toba caldera (Jaxybulatov et al., 2014) and Yellow Stone caldera (Jiang et al., 2018) or volcanoes at the rim of large calderas such as Kirishima volcanoes. Such discrepancies imply the radial anisotropy generated by a sill complex in the magma reservoir. However, it is not clear whether this feature is common only among volcanoes related to large calderas.

Here, we focused on the possibility that the existence of the radial anisotropy beneath the volcano depends on the stress field: a volcano lying in an extensional stress field likely to show the radial anisotropy. In order to ascertain this hypothesis, three volcanoes in Japan were taken as examples, that is, Kirishima volcanoes in a regionally extensional stress field, Asama volcano in a regionally compressional stress field, and Hakone volcano in a regionally compressional but locally extensional stress field. In this study, we conducted the ambient seismic noise tomography for each of three volcanoes and obtained three-dimensional $V_{SV}$ and $V_{SH}$ structures from a collection of local one-dimensional velocity profiles derived by inverting phase velocities of Rayleigh and Love waves, respectively, at each grid point. Based on the result, we will discuss the relationship between the existence of radial anisotropy in the magma reservoir and the stress field.

## AS25-0467

# A study on the peculiar seismic activity on the island of Vulcano, Italy, between 2021 and 2024

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Burst-like seismic swarms are a typical phenomenon of seismic activity in many volcanic regions. Fluids from hydrothermal systems and/or magma reservoirs can produce a variety of signals, from Very Long Period (VLP) events to earthquakes, whose seismic signature varies depending on the characteristics of the source. Periods of volcanic unrests are often accompanied by a high rate of occurrence of different kinds of seismic events, which do not always lead to eruptions. This is what happened on the island of Vulcano, Italy, from September 2021 onwards. A sudden increase in the values of many geochemical and geophysical parameters was measured 131 years after the last eruption. Despite the strong variations, most parameters slowly returned to background levels and no relevant volcanic activity occurred. From a seismic viewpoint, burst-like swarms—with a high occurrence rate of VLP events—were recorded both in the initial phase of the unrest and in the following months. Tectonic seismicity occurred in short-lived swarms well after the onset of the unrest and with magnitude values of up to ML4.6. In this study, we focus on the occurrence of seismic events recorded from 2021 to 2024 in the form of families identified by machine learning applications. The hypocentral locations mostly clustered in the northern part of the island of Vulcano, in the so-called La Fossa Crater. Our results highlight the fundamental role of fluids, such as vapor and gases, which probably enabled the fracturing processes through a network of shallow micro-fractures.

## AS25-0473

# The upper crustal structure and seismicity of the Eifel volcanic region, southwest Germany using Large-N seismic network data

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The Eifel volcanic fields are type-localities for maar eruptions and phonolitic-carbonitic explosive centres, with the last VEI 6 eruption at the Laacher See volcano (LSV) only 13 ka ago. Although the volcano is currently classified as dormant, phenomena such as $CO_2$ degassing, ground uplift, subsidence, and seismic activity have been indicators of potential magmatic processes at depth. From September 2022 to August 2023, a temporary large-N seismic network comprising over 494 station locations was deployed in the Eifel region, specifically around the Laacher See, providing an unprecedented opportunity to better understand the subsurface structures here.

Given the substantial amount of data collected by the Large-N network, we detected more than 1000 microseismic earthquakes using rapid machine learning techniques, including a few deep low-frequency earthquakes. Largest events are used for probabilistic moment tensor inversions to identify active faults. We further selected more than 700 high-quality local earthquakes to perform local earthquake travel-time tomography with 62,696 P-wave and 52,345 S-wave arrivals. The 3-D tomographic Vp and Vp/Vs ratio models of the upper crust resolve a high Vp/Vs ratio, cylindrical anomaly with below average Vp velocities beneath the LSV, which may indicate a fluid bearing or partially melting region. Micro-earthquakes at the margins also indicates that the zones are under high fluid pressure or elevated temperatures. The spatial correlation between this observed anomaly and the deep low-frequency event channel from previous observations suggests that magmatic fluids from deeper sources may still be migrating beneath the LSV and are associated with the anomalous region.

## AS25-0474

# Leaky faults modulated magma ascent and seismicity during the 2022 São Jorge (Azores) volcanic unrest

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Understanding the signatures and mechanisms of failed volcanic eruptions is vital for mapping magma plumbing systems and forecasting volcanic hazards. Geological structures like fractures and faults are key to guiding magma, but their mechanisms remain unclear due to limited 3-D mapping of faults in volcanic regions and sufficiently precise earthquake locations. The triple-junction setting of the Azores Archipelago, where volcanic systems and seismogenic crustal faults coexist, offers a unique window into how faults impact magmatism. Using ~12,000 earthquakes relocated to ultra-high precision with onshore and ocean-bottom seismometer data, along with geodetic observations and seismic autocorrelation imaging, we analyse a failed eruption in 2022 on São Jorge Island. Magma from the upper mantle ascended rapidly and largely aseismically over several days along a crustal fault, before stalling beneath the island edifice. Adjacent seismicity with rotated focal mechanisms suggests that the ascending magma became less buoyant due to devolatilisation, with fluids leaking laterally along the fault zone, triggering an intense, months-long seismic swarm. This study reveals the dual role of fault zones in both facilitating and arresting magma ascent, highlighting the interplay between tectonism and magmatism.

## AS25-0496

# Insights into volcanic seismic high-frequency tremor on Mount Etna reveal implications for its driving mechanisms

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Seismic tremor plays a crucial role in eruption forecasting and is therefore monitored extensively on volcanoes around the world. For this purpose we need to improve our present understanding of tremor's source processes. Traditionally, the generation of volcanic tremor is attributed to processes associated with magma transport or linked to fluid-induced resonance within the volcano plumbing system. In contrast, other studies suggest that fluids may not be required to generate tremor but the weak materials that make up volcanic edifices can experience diffusive failure patterns related to non-localised, low-amplitude seismic events merging into tremor. Small departures from the background stress levels would be sufficient to generate low-amplitude, small-stress-drop events for materials near the brittle-ductile boundary, as demonstrated by numerical models and laboratory experiments. Here, we investigate rare high-frequency tremor data, in the frequency band 10–20 Hz, recorded on the summit of Mount Etna during a large seismo-acoustic deployment during the summer of 2022. We show how insights into the driving mechanisms of the episodic, high-frequency, tremor can be gained from the analysis of the seismo-acoustic energy ratios, which vary significant suggesting different conditions for tremor generation. Additionally, we are able to locate the high-frequency tremor using multi-array beamforming and 3D grid-search algorithms; our results reveal the presence of different source regions, only some of which are associated with degassing. Seismic b-values of tremor episodes seem indicative of the hypothesis that tremor may result from sequences of multiple small-magnitude, very small-stress-drop, individual seismic events in weak material.

## AS25-0499

# Volcano tectonic seismicity at Mt. Etna volcano (Italy) from high-precision earthquake relocations

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This study presents a multi-scale, high-precision relocation of volcano-tectonic seismicity at Mt. Etna (2014- 2023), using an enhanced location procedure which generates travel-time corrections and uses waveform similarity to improve fine-scale precision (NLL-SSST and NLL-coherence techniques). Compared to previous studies, these relocations show improved resolution of distinct patterns of organization and clustering at different space-time scales, and images novel features.

The results confirm some characteristics of Mt. Etna's seismicity, such as its concentration at depths shallower than 10 km, its distribution beneath the volcano's central area and eastern and southwestern flanks, and the absence of seismicity within the high velocity body (HVB), under the central-southeastern flank, known in literature.

Notably, the relocations reveal new seismic features, including dense, nested clusters at shallow depths (ca. 5 km) along main tectonic structures and a tabular seismic structure (10–25 km), dipping NW corresponding to a thrust ramp from regional crustal convergence. Finally, isolated deep clusters with vertical elongation (12–20 km) may indicate magma movement and re-pressurization in the intermediate and deep crust.

## AS25-0511

# Time-lapse imaging of eruptive processes at Nyiragongo volcano using infrasound

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Eruptions at continental basaltic volcanoes, the dominant mode of volcanism on Earth, can take and combine various forms, including lava lakes, lava flows and fountaining, explosions or structural collapses. Recording seismicity is widely recognized as essential for tracking magma movements at depth but must be complemented with other observations for monitoring eruptions, which are by essence atmospheric processes. Aside from a few well-instrumented cases worldwide, accurately reconstructing the precise eruptive mechanisms and chronology is hampered by the lack of detailed visual observations in space and time.

However, because they emit low-pitched inaudible sounds, called infrasounds, any changing and potentially hazardous eruptive activity can be inferred with specialised microphones. Using acoustic numerical modeling, we consider the case study of Nyiragongo volcano (D.R. Congo) to convert infrasound records from local distance up to Kenya (~800 km) into high-resolution time-lapse observations of the catastrophic drainage of the world's largest lava lake on 22 May 2021. The emitted infrasounds also enable us to track fissure openings and lava eruptions along the flank, occurring simultaneously with the lava lake drainage. This striking example highlights how decoding each specific volcano's acoustic signature provides unique information inaccessible to other ground-based instruments, which can be integrated to monitoring and multi-hazard early warning systems.

## AS25-0517

# Dike arrest identification by focal mechanisms reversal: evidence from Etna eruptions

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Understanding the mechanisms controlling dike propagation has always been a central issue in volcano physics. Predicting dike behavior in near real-time remains challenging, particularly in determining when and where a dike will become arrested. Mount Etna provides key case studies of dike arrest during several lateral intrusions, notably in 1989, 2002, and 2008. These events exhibited two common features in the final stages of dike propagation: attenuation of deformation signals and the occurrence of compressive focal mechanisms in the earthquakes. This study examines the 2018 Mount Etna eruption (24–27 December, 2018), well explained by a double-dike intrusion. A first shallower feeder dike originating in the last 3 km beneath the central crater area, and a secondary, deeper and more extensive dike that penetrated the high southern eastern flank and stopped without reaching the final portion of the volcano. We investigate the seismicity associated with this second intrusive episode by analyzing the focal mechanisms of 51 earthquakes with ML≥1.8. The majority of these earthquakes were strike-slip or normal faulting events, but a small number exhibited reverse faulting mechanisms. Interestingly, reverse faulting became more prominent during the final stage of the intrusion, starting from the early hours of December 25. By inverting the focal mechanisms, we identified a change in the local stress-field orientation, suggesting two distinct stress regimes before and after 01:30 UTC on December 25. This transition highlights the importance of recognizing reverse faulting as a key indicator of stress field variations and the potential arrest of dike propagation.

## AS25-0522

# Pre-existing structures control the orientation of strike-slip faulting during the 2021 dike intrusion at Fagradalsfjall, Iceland

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The 2021 Fagradalsfjall inflation and dike intrusion marked the initiation of a new era of volcanism on Iceland's Reykjanes Peninsula. We present a large automatic catalog consisting of more than 80,000 earthquake hypocenters spanning the full period of the dike intrusion, which were derived from seismic data recorded by a dense network of seismometers. The 9–10 km long dike exhibits a two-segment geometry of similar lengths. Linear regression on a relatively relocated subset of over 12,000 earthquakes revealed a strike of 029° with a standard deviation of 2° in the southern segment, and 046° with a standard deviation of 1° in the northernsegment of the dike. A total of 97 detailed fault plane solutions from selected subsets of events provide new insight into the controls on faulting, showing almost exclusively right-lateral strike-slip/oblique-slip faulting associated with the dike intrusion, and a lack of left-lateral strike-slip fault motion. The alignment of fault planes is consistent with the orientation of pre-existing structures, within uncertainty estimates. In light of these observations, we conclude that the likelihood of faulting being related to classical dike tip fracture ahead of the dike tip is low. Instead, our preferred explanation for the dominant controlling factor on the orientation of dike-related faulting is the extensive network of pre-existing structures formed by the active transtensional plate boundary along the Reykjanes Peninsula.

## AS25-0536

# Earthquake clusters at Vulcano Island, Italy, and surrounding areas

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The onset of the volcano unrest on the Island of Vulcano, Italy, in September 2021 became a matter of concern for Italian governmental and scientific institutions involved in monitoring and surveillance. Numerous seismic events linked to hydrothermal processes as well as related to tectonic processes at Vulcano and surrounding areas were recorded. Here we focus on earthquakes and the identification of activated structural elements. The spatial distribution of earthquake hypocenters provides important hints on tectonic elements and their geometries. As small earthquakes occur frequently, their hypocenters are efficient tracers for active tectonic structures. Often hypocenters cluster in volumes described by simple mathematical terms. However, tectonic elements can have complex geometries, e.g., "listric" geometry, or bow-formed structures. The overlapping distribution of seismic events complicates the identification of clear patterns. Therefore, traditional visualization falls short in the presence of complex geometries. A way out resides in Cluster Analysis, where groups of patterns are found considering the distance between patterns. Classic clustering is based on variance and dispersion-based metrics, which represent the scatter of patterns around centroids and where clusters have convex hulls, with a (hyper)spherical or (hyper)ellipsoidal aspect. More complex geometries can be tackled with "Density Based" (DB) Clustering, which can identify clusters of arbitrary shapes. The application of various clustering approaches is shown on hypocenter locations related to earthquakes occurring in the years from 2020 on.

## AS25-0581

# Exploring the Link Between Sea-Level Changes and Spatial Patterns of Global Seismic and Volcanic Activity

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Understanding how ocean tides and sea-level variations influence earthquakes and volcanic eruptions is important for hazard assessment. At a global scale, oceans redistribute mass on Earth's surface, affecting stress fields in the crust. Since many volcanoes are located near or under oceans, it is hypothesised that stresses induced by ocean loading play a critical role in destabilising volcanic systems, potentially triggering eruptions and earthquakes. The weight and movement of water can indeed alter pressure on magma chambers, impacting their stability.

Previous studies identified multidecadal periodicities (20, 30, and 50 years) in volcanic activity and global sea levels, suggesting a connection. This study examines the spatial patterns of eruptions relative to coastal proximity, revealing a consistent trend: Eruptions are concentrated near coasts, decreasing with distance. Across different cycles, about 30% occur within 10 km of the coast, 30% within 50 km, 15% within 100 km, and 25% beyond 100 km. The 20-year cycle exhibits the highest concentration of eruptions near the coast during peak maxima.

While clear temporal correlations exist between sea-level variations and eruption frequency, definitive spatial patterns remain elusive, suggesting additional influencing factors. Further research, using advanced modeling techniques and Geographic Information Systems, is needed to refine our understanding. Interdisciplinary approaches will help uncover more precise connections. These findings contribute to growing evidence that sea-level changes may influence volcanic and seismic hazards in coastal regions.

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## AS25-0587

# Source inversion and clustering of volcano-tectonic earthquakes at Copahue-Caviahue Volcanic Complex, Argentina

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The Copahue-Caviahue Volcanic Complex (CVCC) has had several recent eruptive periods, the last starting in 2012, being the Copahue volcano the most active in Argentina. The CVCC lies in a transition zone linking the right-lateral Liquiñe-Ofqui Fault System and the thrust-fault Antiñir-Copahue fault zone. The region hosts a complex interaction between local and regional faults, hydrothermal activity, and volcanic processes. Investigating such interaction and the local seismicity is crucial to understand the relationship between structures and volcanic-hydrotermal activity. We performed an extensive and detailed seismological analysis based on continuous seismic data from a local network (OAVV-SEGEMAR, OVDAS-SERNAGEOMIN) from May 2018 to December 2023. We report about automatic detection and location, spatiotemporal clustering, moment tensor inversion, and waveform similarity analysis. We first obtained a catalog of 7544 volcano-tectonic (VT) earthquakes, applying Qseek, a state-of-the-art, waveform-based technique that relies on deep neural network-based detection of P and S arrivals and localization of seismicity through a stacking and migration approach. Then, we applied spatial and temporal seismicity clustering using a density-based clustering approach and identified 18 spatio-temporal clusters. We further investigated the seismicity in each cluster by assessing their waveform similarity and identifying a variable number of sub-clusters. Finally, we conducted a waveform-based moment tensor inversion for selected earthquakes. Overall, our analyses illustrate with unprecedented details the complex shallow seismicity at Copahue volcano, which shows different spatio-temporal bursts of activity, including both mainshock-aftershock sequences and swarm episodes, affecting different lineaments and active fault structures.

## AS25-0635

# Shallow rupture earthquakes and seismic processes accompanying uplift at Campi Flegrei caldera, Italy

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Campi Flegrei (CF) is a volcanic system located in a densely populated area west of Naples, Southern Italy. With a long history of eruptions, CF is the largest active caldera system in Europe. The most prominent feature of CF activity is ground deformation (so-called 'bradyseism'), which consists of rapid uplift usually accompanied by seismicity, followed by slow subsidence aseismic phases. The ongoing deformation, which began in 2005, gained an uplift of ~1.4 m while the seismicity exponentially increased, reaching a maximum magnitude Md 4.4 in 2024. In this work we analyze the seismic catalogue from the INGV-Osservatorio Vesuviano, from 2014 to March 2025. For a selected subset of 130 events with Md > 2.5, we perform time-domain, full-waveform Moment Tensor (MT) inversion using data recorded by up to 40 stations within 120 km epicentral range. The inversion is conducted using a probabilistic approach. Different velocity models and frequency bands are adopted for stations located within several distance intervals. We obtain full, deviatoric and double-couple MT solutions for 98 earthquakes, representative of the seismicity present at CF. From waveform similarity we identify 6 earthquake clusters, each characterized by similar locations and focal mechanisms. Most mechanisms indicate normal faulting; offshore events have locations and fault plane orientations which resemble the geometry of the caldera rim, while those in the most active Solfatara region mostly strike WSW-ENE. These results reveal with unprecedented detail the geometry and kinematics of the active fault structures in the Campi Flegrei region, and their relationships with volcano-tectonic lineaments.

## AS25-0644

# Travel time tomography of Aluto Volcano in the Main Ethiopian Rift

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Understanding the structure of the crust and subsurface fluid distribution in volcanic systems is critical for geothermal energy development, volcanic hazard monitoring and mineral exploration. Seismic travel time tomography provides high-resolution images of the subsurface by mapping variations in P- and S-wave velocity structures and their ratio (Vp/Vs), offering insights into the internal structure of the volcano. In this study, we apply local earthquake travel time tomography at Aluto volcano, located in the central Main Ethiopian Rift (MER), and Ethiopia's first pilot site for geothermal energy development.

We analyse seismic data recorded between January 2012 and January 2014, identifying 2,393 local earthquakes mainly along the central part of the caldera and the Wonji Fault Belt (WFB) using non-linear location methods. We selected events with low spatial errors and a signal-to-noise ratio threshold of three or higher for the 3D travel time tomography. By resolving P- and S-wave velocity variations, as well as Vp/Vs anomalies, we aim to delineate zones of fluid saturation and structural heterogeneity. We compute the complete model resolution matrix using direct sparse methods, enabling us to assess the reliability of the tomographic model.

The results of this study are compared with previous studies on the attenuation and conductivity structure of Aluto, collectively providing new insights into the magmatic-hydrothermal system of the Aluto volcano. This study will help to refine geothermal exploration strategies and enhance our understanding of subsurface processes beneath the volcano.

## AS25-0710

# Ojos del Salado volcano: how active is this sleeping giant?

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Ojos del Salado Volcano is a high-altitude volcano located at the intersection of the Central Andean Volcanic Zone and the Pampian Flat Slab. Although the last major eruptions occurred in the Holocene, steam was observed near the summit in 1993, and there are geothermal springs feeding into the Laguna Verde, a hypersaline lake about 25 km NNE of Ojos del Salado. However, little is known about seismic activity near the summit, or the current level of volcanic activity. Following a 2022 pilot study, 29 geophones were deployed around Ojos del Salado and the Laguna Verde for 20 days in February 2024. Geophones were grouped into six sub-arrays allowing the use of array techniques to locate events outside of the network which was limited by national borders and terrain.

We present the locations, magnitudes, and focal mechanisms of events recorded within this temporary network. 51 of the relocated events had magnitude larger than 0, the largest having local magnitude 2.8. Events formed two main clusters, one on the western flank of Ojos del Salado itself, and a smaller cluster just to the north. 29 focal mechanisms were plotted, mainly near the summit. No seismicity was observed near Laguna Verde, and the data showed a lack of the Low-Frequency and Tremor signals that are typical of more active volcanoes. This, combined with a b-value around 1, indicates that although Ojos del Salado is still seismically active, here we observe only a brittle regime and not ductile deformation by magma or fluids intrusions.

## AS25-0765

# The 2022 Seismic Swarm in São Jorge, Azores: Insights into Magmatic Activity

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After 60 years of relative calm, on March 19, 2022, at 5:11 PM, a seismic crisis of 'swarm' type was triggered on the island of São Jorge (Azores, Portugal). The recorded seismic activity reached a peak of 700 events per hour, including an event with a maximum magnitude of 4.0 (Ml). According to the seismic bulletin from the Institute of the Sea and the Atmosphere, the epicenters were distributed following a direction close to the alignment of the island, covering a zone going from Velas untill Pico da Esperança and depths, mainly between 7 and 13 km. With the exception of a single hybrid event, all the detected seismic signals were essentially of a tectonic nature, and the associated focal with the events predominantly strike-slip.

This seismic sequence is attributed to a dike-type magmatic intrusion, as confirmed by InSAR (Interferometric Synthetic Aperture Radar) images and GNSS data, both of which revealed a significant ground displacement patterns indicative of magma movement beneath the lithosphere under the island.

The results of the seismicity and the source analysis of this sequence will be presented. The seismic events composing the sequence came from data collected by the permanent stations of IPMA and the temporary seismic network installed on the islands of São Jorge, Pico, and Faial, having the purpose of monitoring this crisis.

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## AS25-0804

# Distinguishing between pure static offsets and “saw-tooth” shaped very-long period (VLP) displacement at volcanoes

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Very-long-period (VLP) seismic signals on volcanoes are thought to reflect the ground’s response to magmatic fluid transport. Most studies describe them as simple transients resembling a Ricker wavelet, but some report “saw-tooth” shaped displacements with fall times of several hundred seconds. Others suggest a “ramp-shaped” VLP source-time history, highlighting challenges in detecting trends beyond the instrument response corner frequency. Even minimal frequency high-pass filtering can transform a “staircase-shaped” displacement into a “saw-tooth” pattern. Since these interpretations correspond to different conceptual models, distinguishing between them is crucial for understanding VLP seismic activity.

Measuring static displacement offsets in small-amplitude low-frequency seismic events such as LP and VLP signals is challenging. The difficulty increases as the ratio between signal amplitude and dominant period decreases, primarily due to limited instrument bandwidth and long-period noise. Recent studies using a median filter successfully recovered micrometer-scale offsets for LP events with rise times of 1–2 seconds, though for VLP events with rise times of 20–30 seconds, this threshold is significantly higher.

A median filter was chosen because high-pass filters remove static offsets, often converting “ramp” or “staircase” signals into “saw-tooth” patterns. However, median filtering is constrained by its time-window length, making it difficult to capture slowly diminishing “saw-tooth” VLP signals. To address this, we investigate how combining frequency and median filters of different lengths can improve signal interpretation, testing the methodology on synthetic datasets.

## AS25-0809

# Crustal anisotropy variations at Mt. Etna for monitoring local stress perturbations

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Changes in stress can occur swiftly in volcanic environments, especially in an open-conduct volcano. We study the temporal variations of crustal anisotropy at Mt. Etna from 2020 to 2021, aiming to evaluate the effectiveness of applying the shear-wave splitting technique in quasi-real time. Our approach aims to reduce reliance on manual oversight and enhance operational potential for real-time monitoring applications.

We measured the time delay between the fast and slow S waves, and the polarization direction of the faster S wave. The latter gives information on the main direction of the local stress field, and the time delay provides evidence on the average crack density/aspect ratio as well as on the size of the anisotropic volume along the ray path.

In the studied period, the activity at Mt. Etna was characterized, first, by a period of relative quiescence, then followed by an initial intense phase of summit eruptions from February to early April 2021. After a pause of approximately one and a half months, Etna exhibited another phase of lava fountaining from May to July 2021.

The results show measurements of shear-wave splitting coherent with the structural characteristics and stress field of the area. Moreover, we analyzed the temporal behavior of the two observables to explore possible relationships with the summit eruption occurrences. We found that some stations exhibit variations in both observables before the paroxysmal sequence and during the inter-phase period. Interestingly, a simultaneous increase in seismic energy release was detected, suggesting stress accumulation prior to the eruptive activity.

## AS25-0890

# Monitoring seismic velocity changes at Campi Flegrei, Italy, using ambient seismic noise interferometry

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Campi Flegrei is a volcanic field located west of the densely populated area of Naples, Italy. Since 2005 its ground has been rising steadily due to the accumulation of fluids at shallow depths. This uplift is accompanied by increased seismic activity. To track fluid movement, we monitor subtle changes of velocities of seismic waves by exploring ambient seismic noise. Examining different frequency bands, we can observe velocity changes at different depths. We interpret these changes as a monitoring of depth-dependent deformation in addition to the standard monitoring of surface deformation. We observe a velocity decrease in the long-term trend, presumably due to the extension of the hydrothermal system at shallow depths. To explain the long-term changes, we model a spherical pressure source to simulate volumetric strain changes induced by recent fluid activity. The model explains both, surface and subsurface deformation which leads to the opening of microcracks and pores, resulting in the observed velocity decrease. The short-term velocity changes are mainly driven by seasonal temperature and/or groundwater level changes. We model these seasonal velocity changes based on three different environmental models. Once velocity changes are corrected for seasonal effects, remaining short term velocity changes can be associated with volcanic activity and earthquake swarms.

## AS25-0933

# Near real-time foreshock-aftershock-swarm discrimination during the seismic crisis of 2025 near Santorini volcano, Greece

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In January-March 2025 a seismic cluster between the Santorini and Amorgos islands, South Aegean, was characterized by rapid increase of the activity rate and the earthquake magnitudes until the maximum magnitude ML5.3 occurred on 10 February. Great social unrest was caused. The epicenters gradually moved from SW to NE with mean velocity 3 km/day covering distance of 25 km and aligning with the tectonic faults of the area. During the ongoing seismicity crucial questions were discussed by scientists. Was it a foreshock-aftershock activity or a seismic swarm of volcanic origin? The characterization beforehand of an ongoing seismicity is difficult and only retrospective solutions were proposed. We utilized seismological methods and complex networks theory to re-evaluate on a daily basis the space-time-magnitude seismicity changes and their significance as compared to background seismicity. Since the first cluster days the foreshock pattern was documented, thus weakening the seismic swarm case. Soon after the earthquake of ML5.3 an aftershock decay was detected. No significant epicenters migration was observed after the mainshock. A cascade mechanism favors the observed foreshock properties. Mechanisms of seismicity driven by hydraulic diffusion does not account for the epicenters migration. An explanation of the rapid sequence increase could be that its occurrence was facilitated by the highly fractured southern segment of the large Mw7.7 earthquake that ruptured the area on 9 July 1956. The January-March 2025 activity was a good opportunity to show how to decipher the type of an ongoing seismicity cluster and discriminate between foreshocks, aftershocks and swarms beforehand.

## AS25-0974

# Terceira island, Azores: crustal imaging and correlation with volcano-tectonic structures and seismicity

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Terceira is a volcanic Island located at the tectonic triple junction of the Azores, between the America, Eurasia and Africa plates. The main active volcanic structure is the Santa Barbara volcano to the west of the island, and the island is divided by a WNW-ESE fissural volcanic system, north of Santa Bárbara, crossing mid-island the active Guilherme Moniz volcano, and to the SW the extinct Cinco Picos volcano. Pico Alto, another active volcano, is located north of the fissural system. This complex geodynamic framework results in several volcanic and seismic events impacting the island.

In 2019–2020, a dense temporary seismic increased the minimum detection threshold of the island seismicity. The recorded dataset allowed us to obtain a 3D tomographic model of the island, offering a detailed characterisation of the seismicity and its correlation with the crustal structure and tectonic stress regime.

All these volcanic features present variable Vp and Vp/Vs tomographic signatures, and significant seismicity up to ~6 km depths. The strongest signals are associated with the active volcanic structures; other weaker signals with either low resolution or inactivity. A relatively high number of very shallow and low magnitude events are present around the area of the geothermal powerplant, located between the Pico Alto and Guilherme Moniz volcanoes.

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## AS25-1009

# Constraining the source of eruptive tremor during the 2021 Tajogaite eruption using seismic array analysis and synthetic simulations

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The 2021 Tajogaite eruption in La Palma, Spain, was extensively monitored, including two small-aperture seismic arrays located 4 km SE and 2 km NE of the eruption site. We apply a time-domain method to estimate the apparent slowness vectors in the 1.6–3.2 Hz band. We identify a persistent tremor with variable coherence and apparent slowness around 1.0–1.2 s/km, impinging on the arrays from directions of ~300 and 260ºN, respectively. These directions are slightly deviated from the active vents, and therefore geometrical locations based on back-azimuths point to a source area relatively distant (~1–4 km NW) from the eruptive vents. Additionally, we identify temporal variations in the propagation azimuths that suggest an apparent migration of the tremor source during October 2021. We use a finite difference method to simulate the evolution of the seismic wavefield, using a 1.5 Hz source time function and time series of point sources mimicking the long-lasting character of volcanic tremor. In this way, we obtain a realistic synthetic slowness vector model that takes into account the effects of volcano topography and 3D velocity structure. Our results show that the tremor originated from an extensive source region several hundreds of meters westward from the main crater, which migrates to the southwest. These findings highlight that the tremor wavefield reflects multiple processes within the magmatic plumbing system feeding the eruption, providing critical insights into volcano dynamics.

## AS25-1109

# Seismic Imaging in highly scattering Volcanic Environments using Fourier Neural Operators

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Many key challenges in volcano seismology stem from wavefield scattering due to strong impedance changes in the subsurface. These are accentuated by along-path effects from environmental noise, rugous topography, tremor and more, all of which result in significant codas observed in recorded seismograms. A main challenge for seismic inversion in volcanic environments is utilising these information-rich codas to recover seismic velocity models on length scales of the smallest significant heterogeneities. This research uses machine learning methods to that end.

Fourier Neural Operators (FNO), our machine learning model of choice, can make predictions of physical system states. Previous studies have demonstrated that geologically plausible velocity models can be recovered by FNOs from forward-modelled seismograms. However, an outstanding challenge for FNO research is to progress the successful performance of FNOs, trained on synthetic velocity models and seismograms, to make robust velocity model predictions from field-gathered seismic data.

In this research we create a large population of velocity models with statistically-derived perturbations designed to represent heterogeneity on length scales observed for volcanic rocks, informed by field measurements such as petrophysical logs. Full waveform modelling is used to produce a seismogram set for each velocity model. Each forward-modelled wavefield includes viscoelastic attenuation with appropriate Q factors for volcanic environments. We train an FNO to predict velocity models from input seismic records and present seismogram-to-model performance to date. We address the resolution limits of the FNO-predicted velocity models and discuss their possible applications to improve understanding of physical volcanic processes in full.

## AS25-1161

# New Insights into Wudalianchi-Erkeshan-Keluo Volcanic Belt in Northeast China from Joint Inversion of Surface Waves and Receiver Functions

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The Wudalianchi-Erkeshan-Keluo (WEK) volcanic belt is one of the youngest volcanic clusters among the Cenozoic intraplate volcanoes in Northeast China. With data from 88 seismic stations, we construct a high-resolution S-wave velocity structure of the WEK volcanic belt, using joint inversion of receiver functions and ambient noise for the crust, ambient noise and teleseismic surface wave tomography for the upper mantle structure. We find a prominent low-velocity anomaly at 8–15 km depth beneath the Wudalianchi volcanic cluster, suggesting the presence of a crustal magma chamber. A prominent channel-like low-velocity body that extends from the Moho to a depth of 100 km directly beneath the WEK volcanoes is also found. We further find that the lithosphere beneath the WEK volcanoes thickens abruptly from ~80 to ~110 km. When the background asthenospheric flow in Northeast China encounters sharp changes in lithosphere thickness beneath the WEK volcanoes, it produces locally turbulent flow, and the upwelling molten material from the asthenosphere accumulated in the uppermost mantle forms the magma chamber and volcanoes. This study provided a piece of evidence that WEK volcanic belt may be derived from the same mantle magmatic source. This study is supported by National Natural Science Foundation of China (grants41474040, 41530212, 42004033).

## AS25-1178

# Seismological insights into the 2024–2025 Santorini-Amorgos sequence through a high-resolution earthquake and moment tensor catalog

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At the end of January 2025, intense seismic activity emerged in the broader Santorini-Amorgos region (Greece), causing unrest among residents of nearby islands. However, this was not an isolated event, as numerous minor seismic events had been recorded on Santorini Island over the preceding six months. The entire area under unrest is located in the Santorini volcanic center, part of the Hellenic Volcanic Arc, that hosts Santorini caldera and the Kolumbo submarine volcano. In this study, we conduct a detailed analysis of the seismic activity by utilizing existing automated workflows to develop high-quality earthquake and moment tensor catalogs. A machine-learning-based catalog was created from scratch by analyzing continuous data from the available seismic network. This approach successfully identified thousands of additional events compared to agency catalogs and significantly reduced the observed magnitude of completeness. The event's locations were further refined through absolute and relative relocation revealing the geometry of structures activated during the crisis. Furthermore, we calculated a comprehensive catalog of full moment tensors, with most events exhibiting positive ISO and CLVD components. Based on these results, we aim to analyze the nature and evolution of the seismic activity, suggesting a shear-opening source process linked to magma migration. Additionally, we seek to classify micro-earthquake signals and assess the current state of the seismic crisis.

## AS25-1221

# Characterization of the recent activity of Poas volcano, Costa Rica, during February-March 2024 using near-source seismic arrays

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Poas volcano, Costa Rica, has an active crater with an acidic lake and frequent phreatomagmatic explosions. Since 2022 the level of the lake has reduced to minimum levels, with an increase in the number and intensity of the explosions, that are often accompanied by high-amplitude volcanic tremor. During February-March 2024 we deployed two small-aperture seismic arrays near the active crater of Poas to analyze the wavefield produced by the crateric activity and constrain the source location of volcanic tremor. The arrays were composed by 8 three-component, short-period nodes and 1 broadband seismic station. The arrays were located about 600 m east and 750 m north of the active crater, respectively, with a configuration defined by the expected wavelengths of the signals and the topographic and logistic limitations. The analysis shows a persistent tremor source at about 3–5 Hz, generating wavefronts that propagate across the arrays with apparent slowness around 1 s/km. The main back-azimuths point towards the crater, which allows to obtain an accurate source location and address the possible changes in source position and depth. Additionally, there are waves impinging from other back-azimuths, probably related to scattering of the wavefield. The data contain also multiple discrete events related to phreatic explosions, with smaller values of apparent slowness pointing to a deeper origin in the volcanic conduit. This study will help us understand the relationship and interactions between the volcanic and hydrothermal systems of Poas volcano.

## AS25-1226

# Study of moment tensors for the seismovolcanic crisis in São Jorge, Azores, in 2022

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On 19th March 2022, a seismovolcanic crisis began on the island of São Jorge – Azores, a region with a record of historical earthquakes and eruptions. A seismic swarm in a volcanic region can indicate an increase in internal activity, which could be a precursor to a volcanic eruption. The recorded earthquakes could be caused by the movement of fluids at depth, such as magma, within the volcanic system that forms the island, or simply by tectonic deformation in the lithosphere. With the data from the local catalogue of the Instituto Português do Mar e da Atmosfera (IPMA, I.P.) and Instituto Dom Luiz (IDL), the aim of this work is to identify the kinematics of the recorded events of magnitude , using the SEISAN software to calculate the focal mechanisms using the polarity method and the Grond software for the probabilistic inversion of the moment tensor. In particular, the aim is to understand if there is a volumetric component associated with the earthquakes or if they display only a shear component. Preliminary results show a spatial evolution of the hypocentres that is compatible with the evolution/migration of fluids at depth during the seismic crisis, and focal mechanisms indicate a predominantly left-lateral movement, with an intriguing relationship with the regional tectonic stress field.

## AS25-1234

# Automatic ML Catalogs in Action: Mapping Grindavík Dyke Growth, Iceland, in High Detail

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The running volcanic activity in the Grindavík area of the Reykjanes Peninsula, Iceland, began in November 2023, when an intensive seismic swarm activated the Reykjanes oblique rift zone. On 10 November, the seismicity highlighted a narrow NE trending zone of about 15 km in length, which was accompanied by rapid subsidence resulting in the formation of a graben 9 km long and up to 4 km wide and dyke formation beneath the graben. The seismic swarm continued until 18 December, when the first Sundhnúkur eruption of the ongoing series began.

We present high-resolution automatic relocations imaging the volcanic activity in Reykjanes, Iceland, using a data-driven qseek framework. It comprises an ML picker and a volume grid search based on a travel time model to stack and correlate individual arrivals of seismic energy to locate events. This replaces the functionality of the phase associator and works efficiently thanks to implementing a hierarchical oct-tree.

We focus on the intense seismicity during the rapid intrusion of a 15 km-long dike in November 2023 and the pre-eruptive seismicity of the fissure eruption of 18 December 2023 near Sundhnúkur. We compare the ML catalogue performance delivered by qseek against established methods and reference catalogues. We also analyse in detail the seismicity migration marking the growth of the 10 November 2023 dyke and the 18 December 2023 pre-eruption seismicity to understand the underlying processes better.

## AS25-1237

# The unforeseen 2025 volcano-tectonic cascade at Santorini-Kolumbo

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An intense volcano-tectonic earthquake crisis escalated offshore the island of Santorini, Greece, on 27 January 2025. Seismicity in the region results from a complex interplay between neighbouring dynamic volcanic systems and regional-scale extensional tectonics, which have historically produced several highly explosive eruptions1,2 and devastating earthquake hazards3, as well as seismic swarms in recent years4–7. The 2025 earthquake crisis mainly affected the Anhydros block, challenging the interpretation of the region's volcano-tectonic framework. We integrate marine geophysical data and onshore seismic and geodetic measurements to reconstruct subsurface magma migration and study the coupling of migration and storage and faults during the crisis. Seismicity indicates the failure of a mid-crustal magma reservoir northeast of Santorini, coinciding with a magma-filled dike propagating into the highly faulted Anhydros block, activating existing fault systems. Deformation modelling indicates that ~0.6 km3 of magma intruded as a 25 km-long dike, reactivating major regional faults and arresting 5–6 km below the seafloor. The magma accumulation may trigger a submarine volcanic eruption when reactivated. It may indicate the birth of a new magma chamber that will play a role in future phases of volcanic activity.

## AS25-1292

# Anatomy of seismo-tectono-volcanic interactions on Iceland's Reykjanes Peninsula (2021–2025)

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We investigate relation between tectonic and magmatic processes during the 2021–2025 plate boundary unrest in the Grindavík area of Reykjanes Peninsula, SW Iceland, integrating high-resolution earthquake locations, focal mechanisms, GPS data, surface deformation observations, and volcanic output. We analyzed how a 4-meter extension was accommodated through 12 extensional events, high-rate seismicity and volcanic eruptions. Focusing on the October-November 2023 graben formation event we determined precise locations of 8000+ swarm earthquakes based on automatic picks and analyzed focal mechanisms of 3000+ events and compared these to surface deformation. The 2023 graben formation coincided with an intense seismic swarm, whose location and faulting type aligned with surface ruptures. We propose a model linking tectonic stress and dike intrusions, suggesting that magma availability, rather than extension magnitude, controls eruptive volumes. These findings provide new insights into rifting, faulting, and magmatism in transtensional environments, with implications for volcanic hazard assessment at mid ocean ridges.

## AS25-1301

# Will the 10 March 2025 M6.5 transform fault earthquake at Jan Mayen trigger an eruption?

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On 10 March 2025, a M6.5 earthquake occurred along the Jan Mayen Fracture Zone, an oceanic transform system in the North Atlantic. The fracture zone passes just north of the island Jan Mayen that hosts the Beerenberg volcano, which last erupted in 1985. The 2025 earthquake ruptured a segment of the fracture zone closest to Jan Mayen that had not seen a significant event since the 1980s. The event was followed by intense aftershock activity that lasted for weeks. We considered that the occurrence of such a large event close to the volcano could potentially trigger volcanic activity. On March 18, the day before the IASPEI abstract deadline, the seismicity characteristics changed abruptly and a swarm of events started to appear closer to one of the seismic stations on the island. These events may be an indication of magmatic changes at Beerenberg. Depending on how this continues, this presentation will focus on the interaction between transform fault earthquake and volcano.

## AS25-1335

# Multi-scale seismic imaging of the Icelandic lithosphere: a focus on Askja and the Northern Volcanic Zone

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Askja volcano, located in Iceland's Northern Volcanic Zone (NVZ), lies at the confluence of the Mid-Atlantic Ridge and a deep mantle plume, creating a region of significant volcanic and tectonic complexity. Imaging the underlying magmatic systems will provide a more profound understanding of how the volcanic plumbing structure in the crust is connected to the deeper-rooted sources in the mantle.

This study utilises seismic data collected from over 120 stations around Askja and the surrounding NVZ, with data spanning from the 1990s to the present. Our approach is to jointly invert body wave arrival times from teleseismic, regional and local events using the Fast-Marching Tomography method as implemented in the FMTOMO package. Using multiple classes of body waves, coupled with the dense network coverage, should provide the opportunity to resolve lithospheric structures down to depths of ~100 km.

Preliminary teleseismic results have identified approximately 400 P-wave events, with slightly fewer S-waves, both of which have a good global distribution and a range of azimuths. The P-wave residual patterns are found to be coherent as a function of source region, with residuals as large as ±0.5 seconds. S-wave residuals exhibit similar spatial patterns but are significantly larger, with some reaching ±2 seconds. The coherent nature of the P- and S-wave residual stacks suggests that the lateral variations in structure in the crust and upper mantle are the main contributors to the residual patterns observed. Our results will provide insight into the crust-mantle plumbing system that is driving volcanic activity in the region.

## AS25-1364

# Entrapped magmatic fluids along a pre-existing tectonic fault: the 2025 Santorini-Amorgos seismic crisis

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In January-March 2025, a highly active seismic swarm struck the Santorini-Amorgos segment of the Hellenic volcanic arc in the Eastern Mediterranean. 14 earthquakes had magnitudes exceeding 5.0, with the largest at M 5.3. To determine the physical processes triggering the swarm, we characterise the earthquakes in detail. We detected events using manual and machine-learning arrival time picks. Our workflow yields ~34,000 events, which we relocate using the recently developed, multi-scale high-precision NLL-SSST-coherence method. Nearly all seismicity aligns well with the Santorini-Amorgos fault zone, mainly within depths of 4 to 14 km which agrees with seismogenic depth estimates for the Hellenic backarc. The earliest seismicity occurs beneath Santorini, then jumps ~20 km to the northeast, leading to the most active segment of the seismic swarm. The zone of seismicity generally expands to the northeast but involves several jumps and repeated back-propagation up to 10 km to the southwest and northeast.

Using a novel seismicity-stress method, we use the distribution of our dense, high-precision seismicity for space-time imaging of potential source mechanisms, assuming Coulomb stress transfer. We find that the seismicity most coherently images tensile opening along a vertical plane striking N45° E, with tensile opening underlying the seismicity at >10 km depth. We interpret that the seismicity was caused by a deep, ~20 km long, laterally- (and back-) propagating magmatic dike along the deep Santorini-Amorgos fault zone, consistent with GNSS observations. We also discuss the robustness of potential, previously reported non-double-couple faulting mechanisms, further constraining our interpretation.

## AS25-1375

# Shear Wave Velocity Variation During the Seismic Swarm Preceding the 2021 Eruption in Fagradalsfjall, Iceland

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The 2021 eruption at Fagradalsfjall, Iceland, was preceded by an intense seismic swarm, providing a valuable opportunity to investigate subsurface magmatic processes. In this study, we analyze shear wave velocity (Vs) variations during the pre-eruption seismic sequence using coda wave interferometry (CWI). This method employs intersource interferometry, where scattered coda waves from closely spaced earthquakes are cross-correlated to extract interevent travel times. Given the high density of seismic events in the swarm, this technique offers superior spatial resolution compared to traditional tomography.

We utilize continuous seismic data from the REYKJANET network, filtering waveforms between 10–40 Hz and selecting coda time windows from 1 to 50 seconds after the S-wave arrival. Data normalization and phase-weighted stacking enhance signal coherence while minimizing noise. Pairs of earthquakes with interevent distances exceeding 1 km are excluded to maximize scattered wave contributions. By clustering events based on temporal evolution, we track shear wave velocity changes over time.

Our results provide insight into subsurface stress redistribution and magma migration prior to the eruption. This approach complements previous analyses of Vp/Vs ratio variations using the Double-Difference Wadati method and confirms the feasibility of using CWI for high-resolution monitoring of seismic velocity changes. The findings contribute to improved eruption forecasting and can be extended to future seismic swarms in the region.

## AS25-1393

# The role of weak compliant rocks in the seismic response of the upper volcanic edifice

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The upper volcanic edifice plays an important role in shaping the final stage of magma migration toward the Earth's surface. This process is expected to produce a distinct seismic response, enabling it to be tracked through the shallow subsurface. As a result, shallow Long Period (LP) seismicity and volcanic tremor are closely monitored for hazard assessment. However, a detailed examination of LP seismicity and tremor signals reveals that these phenomena can occur without the movement of migrating fluids. Additionally, it has long been observed that eruptions are often preceded by a brief period of quiescence—an unexpected occurrence if fluid-driven seismicity were progressing toward the surface. This study explores the impact of compliant and weak rocks, which are common in upper volcanic settings, on seismic activity. Our findings suggest that many pre-eruptive seismic characteristics can be explained by the rheology of upper edifice rocks and hence is not a reliable indicator of the presence of migrating fluids.

## AS25-1400

# DAS Deployment for Real-Time Earthquake and Volcano Monitoring on the Reykjanes Peninsula SW Iceland

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We present the first Icelandic Distributed Acoustic Sensing (DAS) deployment, operated by the Icelandic Meteorological Office, a significant advancement in real-time monitoring of volcanic and seismic activity in Iceland. DAS methodology utilizes continuous optical fibers, covering tens of kilometers, as highly sensitive arrays of seismo-acoustic sensors. This exceptional spatial and temporal resolution of DAS enables the detection and characterization of subtle volcanic and seismic signals with high accuracy, making it suitable for eruption monitoring in the Reykjanes Peninsula. Thus, to enhance monitoring of the ongoing volcanic crisis at Grindavík, we installed a real-time early warning system that utilizes the DAS data and delivers alerts to the Icelandic Meteorological Office natural hazards monitoring room. We deployed an ASN OptoDAS interrogator, a long-range and low-noise instrument with low-frequency detection capability. We simultaneously monitor two telecommunication fiber-optic cables in collaboration with Ljósleiðarinn, using a combined length of roughly 150 km, extending from Ásbrú-Keflavík to Þorlákshöfn in the south, as well as to Hafnarfjörður in the north. The high sensor density, with measurements every 10 meters and a temporal sampling frequency of 100 Hz, allows the detection of diverse signals, including volcanic processes and microseismicity. The DAS dataset, acquired over two months, demonstrates the significance of DAS in ensuring continuous volcano monitoring during periods of intense weather noise degrading traditional seismometer performance. We discuss our overall operational experience, specifically the application of the early warning system, initial results and quality checks performed on the dataset.

## AS25-1402

# Beneath the Surface: Tracking Magmatic Unrest at Santa Bárbara Volcano (Azores)

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Terceira Island (Azores Archipelago) rests in a complex geodynamic setting shaped by the interaction of the Eurasian, Nubian (African), and North American plates. Seismicity on the island is mainly associated with active volcanic systems, including the Santa Bárbara Volcano in the western part of the island and the younger WNW-ESE trending Fissural Zone Volcanic System, which overlies the Pico Alto and Caldeira Guilherme Moniz volcanoes, terminating in the southeast at the oldest Cinco Picos Volcano.

We analyse data from two temporary seismic networks (2019–2020 and 10/2023–present) alongside the National Seismic Network. Machine learning helps in detecting events, the earthquake locations were refined with hypoDD and NonLinLoc codes, shedding light on the magmatic system beneath the volcano.

A seismic swarm began at Santa Bárbara in August 2022 and has remained above background levels. Most earthquakes are below ML 3, with occasional events up to ML 4, and notable occurrences in September 2023 (Mw 4.5, Mw 4.3), January 2024 (ML 4.5), and January 2025 (ML 4.3).

We identified long-period, hybrid, and volcano-tectonic earthquakes, along with a northward migration of seismicity since 2019. Focal mechanism solutions explore stress transfer between Santa Bárbara and the Fissural Zone. We're applying local earthquake tomography to image the island's structure further (see Dias et al. 2025, IASPEI-IAGA 2025 communication).

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## AS25-1406

# Determining source mechanism of shallow events via a Bayesian inference with data and theory uncertainty treatment

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Determining source dynamics of shallow earthquakes from observed waveforms via geophysical inversion remains challenging. Firstly, a broader range of physical processes near the Earth's surface requires a more generalized source representation. A composite source of two common source models, moment tensor (MT) and single force (SF), is necessary to describe the physics of some problems, e.g., volcanic earthquakes. Secondly, shallow events often exhibit significant source-type ambiguity between the MT's isotropic and vertical compensated-linear-vector-dipole components. The explosive-like MT and vertical force also show a trade-off. Therefore, thoroughly and effectively exploring all potential source types is essential to characterize the ambiguity properly. Thirdly, a rigorous uncertainty treatment for theory error primarily due to the imperfect knowledge of Earth's structure and data noise can improve the resolvability of source parameters but has proven challenging in actual implementation. Here, we propose an advanced Bayesian inference to mitigate the abovementioned challenges. We design the Bayesian MT inversion scheme with affine-invariant ensemble samplers treating data noise and theory error as free parameters and benchmark it with five shallow-buried DPRK explosions, confirming their explosive nature. Then, we extend it to a joint MT and SF inversion in treating the catastrophic 2022 Hunga (Tonga) volcano eruption. The results support a composite source of a shallow underwater explosion and a striking upward force possibly caused by the abrupt vertical displacement of the water body above the volcano. This current development sets the foundation for future endeavors to characterize the nature of shallow earthquakes in various geological environments.

## AS25-1424

# Detection, Characterization, and Interpretation of Diverse Seismic Signals in Submarine Hotspot-Ridge Interaction Settings

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Ocean bottom seismometers (OBS) placed on mid-ocean ridges record a broad spectrum of signals that originate from diverse solid Earth processes and other sources, including whale calls, anthropogenic activity, and ocean noise. Detection, discrimination, and characterization of these signals is challenging because they are often complex and concurrently recorded. This is especially true during eruptions. Furthermore, phase conversions and reverberations complicate the interpretation of seismic phases. Here we show examples from the East Pacific Rise at 9°50'N and from Axial Seamount, a submarine volcano on the Juan de Fuca Ridge which last erupted in April 2015. We focus on the 7-station, cabled OBS network at Axial where we automatically detect and characterize events in real-time using an extensive suite of methods: kurtosis, machine learning (ML) and cross-correlation for event detection as well as polarity, phase arrival and delay time measurement; grid search and double-differences for hypocenter location and relocation, respectively. In addition, we use unsupervised ML to characterize time-dependent variations in spectrograms to discriminate between different source origins and types of brittle failure. For example, we detect and monitor precursory mixed frequency earthquakes which were first observed before the 2015 eruption, and impulsive seafloor events that track lava flow during eruptions. These observations, combined with ambient noise and active source seismics, reveal insight into the structure, mechanics, and dynamics of Axial Seamount, and help forecast and monitor the timing of Axial's next, imminent eruption.

## S11 Disaster risk reduction for the built environment and resilient societies

### AS25-0010

# Integrating Local Wisdom and Modern Strategies for Disaster Risk Reduction: Building Resilient Communities and Sustainable Built Environments in Indonesia

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Indonesia, as one of the most disaster-prone nations globally, exemplifies the urgent need to integrate traditional wisdom with advanced methodologies to achieve comprehensive disaster risk reduction (DRR). This study critically examines the synergies between indigenous knowledge systems and modern scientific approaches in enhancing the resilience of communities and the built environment. Drawing on case studies from regions such as Yogyakarta, renowned for its community-based earthquake preparedness, and Jakarta, characterized by its innovative yet locally grounded flood mitigation strategies, the research explores the efficacy of hybrid DRR frameworks. Key findings highlight the pivotal role of indigenous practices, such as *rumah panggung* in Sumatra and the *surjan* agricultural system in Java, mitigating disaster impacts through adaptive land-use planning and resource management. Simultaneously, advanced technologies, including geospatial modeling, machine learning for vulnerability assessments, and multi-hazard risk simulations, offer nuanced insights into urban and rural disaster dynamics. However, the study identifies persistent challenges, including the erosion of local practices due to modernization, limited documentation of traditional knowledge, and gaps in integrating these practices into institutional DRR frameworks. This research underscores the transformative potential of participatory planning that harmonizes local and scientific knowledge, fostering community-driven resilience while leveraging institutional and technological support. Policy recommendations advocate for embedding traditional knowledge within national and regional DRR policies, advancing capacity-building initiatives for local leadership, and promoting multi-stakeholder collaboration to address complex disaster risks. By synthesizing traditional wisdom with cutting-edge innovations, this study provides a robust framework for strengthening disaster resilience and adaptive capacity in Indonesia's multifaceted socio-ecological landscape.

## AS25-0011

# The Seismotectonic Model of Central Southern Africa: Implications for Seismic hazard analysis

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With an increasing need for seismic hazard assessment and risk mitigation in the region, understanding the underlying tectonic framework and seismic activity is imperative. In order to develop the seismotectonic model, geological, structural geology, geophysical and seismological data were integrated. The model delineates the major tectonic features and their influence on seismicity in the region. By employing various geospatial techniques, five seismic source zones were delineated and characterized in this study. The findings provided valuable insights into the seismotectonic framework of central Southern African region, offering a basis for seismic hazard and risk evaluation and mitigation strategies. The developed model serves as a fundamental tool for earthquake preparedness, land-use planning, and infrastructure resilience in the region. This study contributes to the broader understanding of intraplate seismicity and tectonic dynamics in continental interiors, with implications for seismotectonic studies worldwide. It is hoped that the information in the seismotectonic map will contribute to the preparation of more accurate hazard assessments for Southern Africa. However, efforts continue to collect and improve collection methods of historical and instrumental seismicity data, as well as geological information to improve the available seismotectonic data for this region.

## AS25-0061

# Earthquake scenarios for the city of Sofia

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Among the geohazards seismic hazard dominates with regard to its social and economic effects on human life and the urban environment. The earthquakes are the most destructive natural phenomenon with sudden onset and rapidly spread impacts affecting large areas In the present study both deterministic and probabilistic earthquake ground-motion scenarios for the city of Sofia (the capital of Bulgaria) are presented. The city is situated in the center of the Sofia area that is the most populated, industrial and cultural region of Bulgaria that faces considerable earthquake risk. In nowadays the city of Sofia is characterized by a long quiescence for strong events and a reduced number of small earthquakes. A strong earthquake in the Sofia area can have disastrous consequences in a large region.

The main objective of the study is to integrate basic geo-datasets and to assess the seismic hazard and using GIS to provide a basis for disaster management of the city of Sofia.

The assessment of seismic hazard and generation of earthquake scenarios is the first step of seismic risk evaluation. Successful preventive measures, quick response to natural disaster and planning of post-earthquake activities are based on scenarios of expected damage, destruction and casualties from predicted strong seismic impacts.

Spatial distribution of the obtained results is available in GIS format and can be used not only for scientific purposes but also for practical measures to reduce the risk and limit the consequences of a future strong earthquake.

## AS25-0085

# Seismic hazard assessment: Key developments and challenges in India

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With over 65% of its land area prone to earthquakes, India is one of the most seismically active nations in the world. The country has experienced four great (M8 and above) and many large earthquakes in the past. These events have caused enormous loss of lives and extensive damage to infrastructure. The primary cause for such a situation may be the population burst and the unsystematic expansion of towns, necessitating the development of adequate tools to prevent losses due to future events. To a large extent, the earthquake hazard can be mitigated by adequately assessing it at local levels (i.e., microzonation), refining building codes by integrating research findings, and ensuring their effective implementation. In India, such studies were initiated over two decades back, and microzonation maps for a few important cities, namely, Delhi, Bangalore, Guwahati, Kolkata, Ahmedabad, Sikkim, and Jabalpur, are now in the public domain. Also, work on eight cities in the Himalayan foothills is in the advanced completion stage.

Cities and towns across diverse landforms, i.e., mountainous regions, foothills, river plains, and coastal areas, pose varied challenges to performing such studies. In modern urban areas, there is hardly any space left to conduct fresh field-based geophysical and geotechnical investigations. The challenge is even greater in historical towns and older cities with heritage structures and religiously significant buildings. The present study summarizes efforts in seismic hazard assessment, key challenges, and future directions in the Indian context.

## AS25-0093

# SimplETAS may improve probabilistic seismic hazard assessment for building code purposes

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Probabilistic seismic hazard analysis (PHSA) traditionally focuses only on mainshocks, modeling their occurrence as a time-invariant Poisson process. This approach implicates the removing of aftershocks through declustering methods, which are inherently non-unique. However, recent studies have demonstrated that aftershocks can contribute significantly to ground shaking, raising concerns that neglecting them may lead to an underestimation of seismic hazard.

In this study, we present a new methodology to account for the entire seismic sequence in PSHA. Unlike existing approaches, our method generates synthetic catalogs that accurately replicate the statistical features of observed seismicity, and ensures consistency and reliability for different return periods. The framework is based on the epidemic-type aftershock sequence (ETAS) model, specifically on its simplified version, SimplETAS, which we use to produce a large ensemble of synthetic catalogs spanning 50 years. For each earthquake in a catalog we pair a plausible seismogenic structure and compute the fault-to-site distance to estimate the corresponding ground shaking intensity value. Finally, we determine the probability of exceeding a given ground shaking threshold as the fraction of catalogs where the intensity is exceeded at least once, bypassing the assumption of a Poisson distribution.

As a first outcome, we obtain seismic hazard curves for the next 50 years for four Italian cities, selected to represent different seismicity levels across the country: L'Aquila, Firenze, Reggio Calabria, and Milano. We then compare these results with the official hazard curves from the national seismic hazard model for Italy, discussing the observed differences.

## AS25-0189

# Crustal Dynamics and Seismic Hazard Studies in West Africa

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No detailed seismic hazard study for West Africa (WA) has ever been conducted because of incomplete earthquake catalogues, which negatively affects the planning and development of critical infrastructure and disaster risk management. This bridges the knowledge gap by updating the current earthquake catalogue for WA. The seismotectonic setting of WA is considered stable continental crust despite several recorded earthquakes occurring in the region, the largest being the 22 June 1939 earthquake of magnitude M6.8 with epicentre in Ghana. However, WA has also been classified as a region of shallow crustal seismicity. Therefore, we investigated both research schools of thought, compared their results using three different ground-motion models (GMMs), and combined to produce each hazard map using logic tree formalism with equal weights. The region was divided into five seismic source zones to compute the earthquake recurrence parameters, with the same parameters computed for the entire WA region. The computed Gutenberg–Richter *b*-value, activity rates λ, and regional maximum possible magnitudes $m_{max}$ for the five zones ranged from 0.84 to 1.0, 0.3–2.1, and 5.2–7.0, respectively. The calculated *b*-value, $\lambda$, and $m_{max}$ for the entire WA were 0.77, 4.1, and 7.2, respectively. Estimated *b*-value of 0.77 falls within the generally accepted range for tectonic seismicity. The seismic hazard predicted by GMMs for stable continental areas was higher than that predicted for shallow crustal seismicity in WA, confirming that the region is characterised by stable continental crust. The highest hazard levels were observed in Ghana, Guinea, Togo, etc, ranging 0.02–0.03 *g*.

## AS25-0243

# Enhancing Multi–Hazard Assessment with the HOMEROS project in central Ionian Islands and the western Gulf of Corinth (Greece)

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In today's interconnected world, communities face a diverse range of hazards, including natural disasters like earthquakes, floods, and landslides, as well as human-induced events. To deal with these risks, the HOMEROS project aims to apply advanced methodologies in seismology, geodesy, and geology, dedicated to enhancing multi-hazard assessment in the seismically active western Gulf of Corinth and central Ionian Islands, Greece. These regions face a complex interplay of geohazards, including earthquakes, landslides, and coastal instability, posing significant risks to communities and infrastructure. To address these challenges, HOMEROS integrates geological, geophysical, geodetic, and remote sensing data contributing to the assessment of hazard interactions and cascading effects, for translating scientific findings into practical applications.

The project aims to a more accurate characterization of multi-hazard dynamics, supporting the development of improved forecasting models and mitigation strategies. By advancing knowledge of multi–hazard interactions, HOMEROS provides valuable insights for policymakers, emergency responders, and researchers. The project's outcomes will contribute to a more resilient society, better prepared to face future natural hazards through data–driven, science–based risk management strategies.

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## AS25-0253

# A transdisciplinary approach to face disaster risk reduction and build resilient societies

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The level of preparedness of European society for disasters have shown strong gaps as witnessed by recent disasters of natural or man-made origin. Hence, it is highly important increasing citizens risk awareness and organizational resilience among people and decision-makers.

It is fundamental to consider human factors, social and organizational aspects supported by scientific results obtained in research on environmental and anthropogenic risks. Whit this perspective, H2020 CORE project has developed a harmonized vision of crisis management awareness and overcoming, through a transdisciplinary collaboration involving the environmental science and social science communities.

Transdisciplinarity aiming to fully understood the complexity of DRR expresses the need for training and research paths capable of going beyond disciplinary boundaries without simply juxtaposing different disciplines (multidisciplinarity) or contaminating them locally (interdisciplinarity). Transdisciplinarity aims to recognize the plurality of knowledge resources and to integrate not only scientific knowledge but also human behavior, experiential and practical knowledge to increase the community response, before, during and after a disaster, increasing their resilience.

Disciplinary specialization has brought a lot of knowledge in DRR. But this knowledge is incapable of grasping multidimensional and global problems as DRR. This approach requires overcoming the disciplinary division in higher education, to train the younger generations in a transdisciplinary transition, making them a sort of "prevention sentinels".

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## AS25-0294

# Design Earthquake Hazard for Near-Fault Regions: Spectrum and Ground Motion

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Near-fault ground motion characteristics depend on the fault mechanism and size of the earthquake. The current protocol of recording strong ground motions inadvertently filters off one important characteristic: residual ground displacement. Hence, the current consideration of near-fault earthquake shaking is based on this "filtered" ground motion. Using these ground motions, some structural design codes worldwide consider near-fault effects in over-simplified ways. As a consequence, important inputs to earthquake resistant design are not considered explicitly, like: (a) rupture mechanism (and associated amplitude, frequency, and duration), and (b) near-fault pulse-like motions along fault-normal and fault-parallel motions.

This study explicitly presents two direct inputs reflecting near-fault actions, namely:

(a) design earthquake spectrum (PSA, PSV and SD) at hard rock and soft soil sites and design residual ground displacement across the fault for use in **structural design**, and

(b) associated ground motion histories for use in **structural assessment**.

Subsequently, a fresh procedure is presented for near-fault earthquake hazard assessment for use in different types of structures in the built environment.

## AS25-0424

# Assessment of Seismic Intensity Distributions through Past Earthquake Comparisons

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Seismic observation networks provide ground motion indices, including seismic intensity and peak ground acceleration. The distribution of these indices is crucial for the assessment of earthquake impacts. Comparisons with past earthquakes are essential for the evaluation of the overall spatial distribution characteristics in post-earthquake assessments.

In this study, we developed a method to evaluate the similarity of seismic intensity distributions between different earthquakes. We analyzed data from the National Research Institute for Earth Science and Disaster Resilience strong motion networks, K-NET and KiK-net. We selected 226 earthquakes in Japan from 1997 to 2019 with a maximum seismic intensity of 5-lower or higher on the Japan Meteorological Agency scale. The observed seismic intensities were interpolated into 381,234 1-km meshes across Japan considering the subsurface structure model. This approach enabled direct comparisons across distributions where the number of available observatories varied.

Independent component analysis was applied to decompose the data into 50 statistically independent element distributions (IEDs), thereby significantly reducing data dimensionality and reconstructing original data. A similarity index was developed based on the contribution values of these IEDs, facilitating visual comparison of seismic intensity distributions. Furthermore, seismic intensity for six test earthquakes was modeled as a linear combination of the IEDs using least-squares fitting, achieving root-mean-square errors below 0.2. This approach enables comparison of seismic intensity distributions between future and past earthquakes. While the method was generally effective, some misidentifications occurred in isolated island regions. This underscores the necessity for improved similarity incorporating additional indices to ensure precision in the analysis.

## AS25-0438

# Efficient ensemble prediction of tsunami inundation using deep learning

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Tsunami inundation forecasts are subjected to the uncertainty primarily attributed to the earthquake slip distribution, particularly for near-field events. We propose a deep learning method to efficiently capture such uncertainties while producing a timely forecast. We train the model using numerous hypothetical scenarios in the study area. In the inference stage, the model requires inputs of tsunami waveforms at specified locations obtained through a Green's functions summation technique. Such an approach allows for rapidly generating tsunami waveforms from the corresponding stochastic slip models. Subsequently, the model runs multiple ensemble tsunami inundation forecasts derived from its varying set of inputs. The final product of the ensemble model includes multiple potential solutions constituting the forecast uncertainty, including the likely best and worst-case values, an essential factor in a forecasting system that is difficult to attain using standard deterministic models.

We apply the model to the South Java region in Indonesia. The total number of hypothetical tsunami scenarios is 630, with the source area originating from the Sunda megathrust of magnitude ranging from Mw 7.6 – Mw 9.2. We consider Pacitan City to be the location for inundation modelling as its location is directly exposed to the anticipated tsunami source. For Green's function calculation, we partition the subduction zone into 300 subfaults. Finally, the prediction uses 100 ensemble members from various stochastic slip realizations of the same estimated earthquake magnitude. The model accuracy is comparable to the deterministic model results but with significantly less computing time of only < 10 s.

## AS25-0577

# A scenario-based approach for evaluating earthquake risk in Reykjanes, Iceland

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The recent identification of the bookshelf fault system in the Reykjanes Peninsula Oblique Rift (RPOR) zone poses a direct threat to the expanding capital region where 2/3rd of Iceland's population resides. Consequently, the earthquake risk in this region is particularly high, underscoring the necessity of conducting a seismic risk assessment (SRA). In this study, we carry out SRA using the state-of-the-art specification of its three key components: (1) seismic hazard assessment (2) vulnerability models and (3) exposure data. Using a recently developed physics-based 3D fault system model for Southwest Iceland, we chose a scenario earthquake of M6.5 at the closest possible distance to the capital region. We establish a dense grid of 1,813 hypothetical stations across RPOR (2*2 km resolution). Then, the horizontal distance to the vertical surface projection of the fault, from each hypothetical station is calculated and the peak ground accelerations (PGAs) are estimated using six Icelandic Bayesian ground motion models, accounting for both aleatory and epistemic uncertainties. Then, the distribution of PGAs is applied to the vulnerability models that were derived from damage data of the 2000 M6.5 and 2008 M6.3 earthquakes in Southwest Iceland. Moreover, the exposure data used in this study contains information on construction years, construction materials, number of storeys, fire insurance value (FIV) and geographical coordinates. The results of this study will be presented in an innovative manner, illustrating damage factor (estimated repair cost divided by FIV), probability of exceeding different damage states, and their associated variability, the first of its kind in Iceland.

## AS25-0663

# Real-time Impact-based Tsunami Forecast Facility

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Bringing together high-performance computing and spatial information sciences, we propose a real-time tsunami inundation and damage forecasting facility to enhance disaster response and management in tsunami-prone communities. The facility first uses the information of the earthquake source parameters which consists of the estimation of L1) earthquake magnitude and the hypocenter, L2) CMT solution, L3) GNSS-based solution, and L4) offshore data assimilation to determine the potential tsunami source model. Given the tsunami source, the system moves on to tsunami propagation and inundation model running on several high-performance computing platforms including the vector supercomputer SX-Aurora in Tohoku University to acquire the estimation of time series of tsunami at offshore/coastal tide gauges to determine tsunami travel and arrival time, extent of inundation zone, maximum flow depth distribution. The implemented tsunami numerical model is TUNAMI code based on the non-linear shallow-water equations discretized by the finite difference method. Given the maximum flow depth distribution, the facility performs GIS analysis to determine the exposed populations, then estimates the numbers of damaged structures by applying the tsunami fragility curve. The results are disseminated as mapping products to responders and stakeholders, e.g. national and regional municipalities, to be utilized for their emergency/response and tsunami disaster management activities. The prototype system starts trial operation in one of the at-risk coastal cities. The forecast facility aims to be utilized to achieve two global agendas of United Nations; 1) Early Warnings for ALL; EW4ALL and 2) Tsunami Ready.

## AS25-0701

# An Algorithm for Probabilistic Seismic Hazard Analysis Integrating Fault Sources and Potential Seismic Source Zones Using Random Sampling

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This study develops a set of probabilistic seismic hazard analysis programs that integrate both traditional two-dimensional potential seismic source zones and three-dimensional fault sources. These programs are designed to be applicable to conventional regional area sources in China while also considering the rupture scale of earthquakes, making them compatible with probabilistic seismic hazard calculations for fault sources. By employing the probabilistic seismic hazard program from the 2015 Seismic Ground Motion Parameters Zonation Map of China and the algorithm presented herein, the regional seismic hazard of the study area, including the Changsha-Zhuzhou-Xiangtan urban agglomeration in Hunan Province with moderate to strong seismic activity, is calculated. Additionally, seismic hazards at different probability levels (return periods of 50.8, 475, and 2475 years) are computed for sites near Changde's near-fault sources and Zhuzhou. Comparative studies reveal that the procedure of the 2015 Seismic Ground Motion Parameters Zonation Map underestimates seismic hazard near three-dimensional fault sources, with this underestimation becoming more pronounced at lower probability levels. By considering the influence of earthquake rupture scale at low exceedance probabilities, the decomposition results for sites near faults indicate that the contribution to seismic hazard differs from the traditional method, which primarily focuses on high-magnitude earthquakes. However, all magnitudes of earthquakes on the fault source can contribute to seismic hazard, with high magnitudes contributing the most. Finally, an example from the Pacific Earthquake Engineering Research Center (PEER) is used to verify the reliability of the algorithm developed in this paper.

## AS25-1008

# Software solutions for seismic network operations and strong-motion monitoring

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Discovery, a software platform developed for seismic digitisers, incorporates tools delivering station configuration and State Of Health (SOH) functionality but extends this to provide an interface for a range of other more advanced applications.

One application is Güralp Data Centre (GDC) which offers instrument configuration to stream data to a central archiving server, where it's saved in 'miniSEED' format and configurable folder structures. This application is particularly important for dealing with large volumes of seismic waveform data. Additionally, data can be transmitted to downstream processors such as Earthworm or SeisComP for more advanced seismic monitoring and analysis. For simplified network management, an integrated VPN/Tunnel circumvents Network Address Translations (NATs) present in internet modems and ADSL connections, allowing the network manager to remotely update digitizer firmware and upload configuration files to multiple units simultaneously. Long-term latency monitoring, network outages and bandwidth usage are captured and displayed in a number of applets. Data integrity can be viewed over time so latency performance can be assessed.

The MAGNA module builds on existing capabilities within GDC to offer a solution integrating seismic monitoring into asset management. MAGNA supports event response, providing guidance after a seismic event by utilising triggered data to produce reports, shake maps and email / SMS alerts. Existing site-specific fragility data for each asset in the network can be applied so that a rapid assessment of likely damage to each facility can be made. As a cloud-based system, users do not need to download and maintain the software, simplifying hardware and networking requirements.

## AS25-1031

# Site response analysis for estimation of seismic site amplification in the city of Durban (South Africa)

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The city of Durban has previously experienced higher than expected ground motions from large distant earthquakes. It is potentially exposed to significant seismic hazard due to seismic site amplification, which needed to be estimated for effective mitigation. Seismic site response analyses were performed at 90 sites in the city. |The equivalent linear approach was implemented, and it computes the ground response of horizontally layered soil deposits subjected to transient and vertically propagating shear waves through a 1D soil column. Seven earthquake time histories together with developed sub-surface models were selected as input parameters to estimate the seismic site amplification at the 90 sites in the city. The uncertainties in ground motion input, variation in the shear wave velocity and variations in the shear modulus reduction and damping curves (i.e. variation of non-linear properties) were carefully modelled. Results obtained from this study were used to prepare maps of peak ground acceleration (PGA) at the surface and amplification factors. The minimum and maximum PGA values at surface are estimated as 0.01 g and 0.30 g respectively. Based on the results of the analysis, the city may sustain amplification in the range of 0.7–4.7 at PGA with high values along the coast. The results indicate that the low shear wave velocity values, weak and soft material at shallow depths are responsible for the higher amplifications observed especially along the coast. Therefore, a site-specific design approach should be adopted for the seismic design of critical structures.

## AS25-1111

# Some contributions towards tsunami risk reduction: a multi-scale and multi-disciplinary landscape

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In this talk I will briefly review some ongoing efforts for tsunami hazard and risk analysis in which I'm involved, and at the interface with risk management and reduction. I will deal with different spatial (from global to site-specific) and temporal (from long-term to early warning) scales, seismic and volcanic tsunami sources, sea-level rise, and combinations between shaking and volcanic phenomena with inundation. I will try to highlight how tsunami hazard and risk analysis is becoming more and more multi-disciplinary and require large collaborations and strong networking which necessarily goes beyond individual background and competences, as further than a range of traditional geophysical disciplines some of these analyses involve different combinations of statistical techniques, machine learning, numerical modelling, agent-based modelling, and high-performance computing. As a consequence, community coordination initiatives such as the Global Tsunami Model (GTM) and the Thematic Core Service (TCS) Tsunami in the European Plate European Plate Observing System European Research Infrastructure Consortium (EPOS-ERIC) become a flywheel of crucial importance, for example to establish good practices or to ensure the necessary interoperability among data and tools from different communities.

## AS25-1131

# Samos becomes Greece's first UNESCO-IOC Tsunami Ready city through preparedness and resilience efforts

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The devastating earthquake of magnitude 7.0 that struck Samos Island of Greece and the Izmir region of Türkiye on October 30, 2020, triggered a tsunami that spread across the Aegean Sea. The earthquake and tsunami caused serious injury and over 100 fatalities in both regions, highlighting the region's seismic and tsunami vulnerability.

The CoastWAVE project, coordinated by UNESCO-IOC and funded by DG-ECHO, started soon after the event, aiming to enhance community preparedness in the NEAM region by implementing the Tsunami Ready Recognition Program (TRRP) in selected counties and sites. The project implementation in Greece, coordinated by the National Observatory of Athens, focused on the town of Samos. In collaboration with the Municipality of Eastern Samos, the local implementation provided the opportunity to develop hazard maps, establish protocols, and foster collaboration with IOC-UNESCO, local authorities, emergency agencies, and stakeholders. This strengthened the strategic alliance between science, emergency management, and the local community, ensuring comprehensive preparedness and risk reduction efforts. The initiative demonstrated the strength of education, preparedness, and stakeholder engagement in building coastal resilience. It provided the platform for the town of Samos to become the first Greek coastal community to achieve UNESCO-IOC's Tsunami Ready recognition.

Other European initiatives like the NEAM-COMMITMENT project funded by DG-ECHO, which aims to develop tools and guidelines for hazard mapping at the national scale and evacuation planning at the local level, can benefit coastal communities in the NEAM regional and beyond in tsunami hazard assessment and improve preparedness and response.

## AS25-1157

# Impact of Uncertainties in Near-Fault Earthquake Hazard Assessment Parameters on Vulnerability, Risk and Resilience of Built Environment

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Near-fault ground motion has two key pulses, namely acceleration and velocity pulses. These pulses can be characterised by five parameters: peak ground values of acceleration and velocity, periods of these acceleration and velocity pulses, and site period. These parameters are affected by several factors other than the traditional epistemic and aleatoric uncertainties, including:

(1) lack of strong ground motion accelerograph data in many countries from near-fault regions,
(2) correction of raw data recorded by the digital strong ground motion accelerographs by protocols meant for analog instruments, leading to overestimation of consideration of earthquake hazard,
(3) mixing up of effects of site period with those of near-fault acceleration and velocity pulses, and
(4) lack of data slip from near-fault regions.

Currently, the near-fault design of the elements of the built environment uses both acceleration demand (e.g., used in buildings and elevated water tanks) and displacement demand (e.g., used in buildings, bridges, long-distance pipelines, cross-country high-tension lines, and tunnels); both are not specifically provided for near-fault regions. Hence, estimates of earthquake risk based on inaccurate inputs are not realistic. Also, the focus should shift from the initial cost to the lifecycle cost (including the retrofit cost). The paper is a sensitivity analysis of near-fault hazard parameters towards reducing risk and enhancing the residence of the built environment.

## AS25-1172

# Disaster preparedness and prevention in Europe, Central Asia and beyond

*Jun Rentschler*[1]

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This presentation will showcase how the World Bank supports governments with preventing, preparing for and recovering from emergencies and natural shocks. The presentation will highlight examples from ongoing engagements in low- and middle-income countries, emphasizing the need for integrated approaches that address multiple natural hazards along with other urgent development priorities. It will highlight insights from the 2024 World Bank and European Commission report on national adaptation needs and costs. Based on this the presentation provides an overview of adaptation cost estimates and methodologies across Europe and showcases an application of best practices in to estimate adaptation needs by 2050 in South-East Europe. It will also highlight how adaptation cost assessments influenced strategic and policy decisions across Europe.

## AS25-1173

# Data-driven empirical tsunami vulnerability modelling and uncertainty propagation

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To accomplish probabilistic tsunami risk analysis (PTRA) within a regional scale, tsunami vulnerability curves play an indispensable role. Empirical tsunami vulnerability curves predict the fatalities and losses given the tsunami intensity measure (IM) based on observed data. Two methodological pathways can be identified for deriving the empirical vulnerability curves: (a) relating the intensity measure directly to the tsunami risk metric data (e.g., fatalities, loss claim data). This is a straightforward modeling approach through adopting suitable regression models. However, its use is limited by data availability. (b) convolving the tsunami empirical fragility curve with the corresponding consequence function and propagating the uncertainties related to both models. Empirical fragility curves are developed for specific classes of buildings and infrastructure at risk based on the pairs of intensity measure (*IM*) and physical damage observations gathered from spatially distributed buildings. We propose a Bayesian data-driven workflow that has the potential to account for the uncertainties in the *IM* estimation at building sites through the generation of a set of possible tsunami simulations representing the uncertainties in tsunami modelling. The workflow considers the hierarchical dependencies between physical damage states, the uncertainty in the fragility parameters, and correlations in fragility parameters for different classes of buildings. This is made possible through a simulation-based Bayesian workflow that uses the adaptive importance sampling technique with Markov chain Monte Carlo simulation (MCMC). Both pathways are demonstrated through vulnerability modelling for past tsunami events such as the 1755 Lisbon Tsunami, 2011 Tohoku Tsunami and the 2018 Sulawesi-Palu Tsunami.

## AS25-1225

# Source and Strong Motion Parameters of Seismic Events (Md ≥ 3) Recorded During the Recent Bradyseismic Crisis at Campi Flegrei

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The Campi Flegrei caldera is experiencing a significant increase in seismic activity due to the ongoing bradyseismic crisis, which began in 2005 and has accelerated since 2023. The rising number and magnitude of earthquakes have heightened public concern, prompting a national government decree to allocate resources for seismic risk mitigation, including building retrofitting. In the identified 'restricted' intervention area—where the most significant effects could manifest if bradyseism persists or intensifies—are estimated 15,516 buildings. Of these, only 58% (9,078) have been recently speedily surveyed for seismic vulnerability (https://mappe.protezionecivile.gov.it/it/mappe-e-dashboards-rischi/campi-flegrei-dashboard-prima-fase-piano-della-vulnerabilita/).

Alarmingly, 80.9% were built before Italy's first seismic code (1981) and designed solely for gravity loads. Additionally, 49.4% are one- or two-story buildings, which are particularly susceptible to high pseudo-acceleration values that defines the response spectra. These numbers highlight a fragile urban environment that requires investigation through reliable methods integrating seismic and structural health monitoring. Characterizing the seismic sources of the most energetic events is essential for understanding the underlying tectonic processes and assessing seismic hazards. This study analyzes the source and strong motion parameters of over 50 events (Md≥3) recorded between 2020 and 2025. Data from ~40 accelerometric and velocimetric stations [of the National Accelerometric Network (RAN), INGV-Vesuvian Observatory (INGV-OV) and Urban Seismic Observatory-Campi Flegrei (OSU-CF)] were processed to retrieve fault plane solutions, seismic moment (M0), source radius (r), and stress drop (Δσ). Additionally, strong motion parameters (PGA, PGV, PSA, ASI) were examined to evaluate seismic impact and hazard, offering insights into rupture processes and fault system dynamics.

## AS25-1293

# Multi-criteria approaches for enhancing disaster shelter preparedness

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Governments and civil protection institutions face major challenges when providing disaster shelters responding to disasters. Sheltering often becomes an open field for delay and improvisation because of insufficient preparedness within disaster risk management (DRM).

Planners commonly identify existing facilities, such as schools and multi-purpose pavilions, as potential shelters in the preparedness stage of the disaster cycle. However, these facilities must meet essential requirements to ensure safe, adequate, and dignified living conditions for disaster victims until permanent housing solutions are restored. This study presents a literature review of multi-criteria approaches to support DRM authorities in anticipating sheltering needs and preparing suitable solutions.

A proposed multi-criteria model is introduced through a three-stage methodology aligned with the principles of collaborative approaches. The first stage identifies the key objectives that disaster shelters should fulfil based on a literature review, analysis of past disasters, and consultations with DRM practitioners. The second stage operationalizes these objectives by defining assessment criteria, establishing relevant metrics, setting target ranges to value metrics results and identifying risk scenarios. The third stage validates the model for specific case studies applied in this study to assess the structural safety of planned shelters in Lisbon. The testing process is iterative and performed in close cooperation with local DRM stakeholders to incorporate their concerns, improve collaboration between science and civil protection actors and foster a culture of disaster preparedness.

Since permanent housing solutions may take several years to implement, this study also examines the advantages and disadvantages of transitional shelters, namely modular construction solutions.

## AS25-1296

# Earthquake early warning for Portugal mainland—performance evaluation 2020/24

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An Earthquake Early Warning System is currently being tested in Portugal mainland. Two seismogenic regions were considered: the south/southwest region, and the Tagus valley region. An independent system was created for each of these regions. This communication deals with the south/southwest region, where a regional approach was followed. To evaluate the intensity estimates produced by the system, three targets were considered: Portuguese Institute for Sea and Atmosphere (IPMA) headquarters in Lisbon, the industrial area in Sines, and the Geophysical Center of S. Teotónio. Based on the events declared by the system, the aim was to determine, on the one hand, whether the first intensity estimates for those targets were close enough to the final estimates based on revised location and magnitude or the manual assigned ones, and on the other, whether estimates were produced that were likely to cause alarm and trigger defensive processes without reason, i.e. false alarms. Functional failures were also addressed. It was concluded that the first intensity estimates at the targets, with a few exceptions (around 7.7%), were reasonably close to the final estimates based on revised solutions and manually assigned intensities, and that no worrying false alarms occurred. The study also suggests that to protect certain locations in relation to the considered seismogenic zone, a local approach of this type of system should be developed and tested.

## AS25-1338

# Use of Simulated Ground Motions for Enhancing Urban Seismic Resilience in Turkey

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Estimation and mitigation of seismic risks in urban regions concern a wide range of authorities including geophysical and earthquake engineers, physical and economic planners as well as insurance companies. Risk mitigation efforts naturally involve inputs from multiple disciplines involving seismic hazard assessment, building fragility models and seismic loss functions. Strong motion records are the key components of these efforts. Nowadays, in addition to the records from past events, the simulated ground motions have the potential to become a prominent thread of earthquake engineering practice due to ever-increasing computational capabilities and advances taking place in earthquake source modeling and site characterization techniques. The use of simulated motions could help explore seismic resilience of urban regions and distributed infrastructure while taking into account complex source and site effects. Additionally, simulated ground motions also have the potential to provide site-specific ground motion datasets for engineers while covering a wide range of parameters including event magnitude and source-to-site distance. In this study, we present the ongoing research on the use of simulated ground motions for seismic damage and loss modeling in Turkey. Both past events and scenario earthquakes are modeled. The study areas of these applications are the urban regions on North Anatolian and East Anatolian fault zones as well as the Aegean Sea region in Turkey. In addition to the current practice, data-related challenges and uncertainties are also discussed.

## AS25-1347

# Every building on Earth

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The built environment is, globally speaking, the largest unknown in the understanding of the effects of disasters and their risk. Detailed knowledge it is necessary for many tasks in disaster risk reduction but also in other fields, e.g. climate-related sustainability, urban planning and management, insurance and re-insurance. While in well-regulated countries cadastral data is available that provides various details about the buildings, in parts of the world such information is lacking and not even the locations of buildings and settlements are known to the authorities. Buildings, the core part of the built environment, can be strongly mixed within small areas in their structural types, sizes, shapes and number of people in them. This heterogeneity cannot adequately be described by classical exposure models that provide aggregated building data over larger areas.

A model that describes the built environment on the scale of each single building has never been accomplished, nor that such a model is dynamic, constantly updating with every change of the input data. Here, we present a high-resolution, open, and dynamic exposure model on the building level. This model is based on volunteered geographic information, predominantly OpenStreetMap and other open data that is created with earth observation and machine learning. The different structural types of buildings per region are taken from open aggregated exposure models or developed from cadastral data. It covers every country and territory globally and is to a large degree building complete with approx. 2.7 billion buildings described in detail.

## AS25-1391

# Understanding Risk Perception in Low-Probability, High-Impact Earthquake Zones

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In regions where earthquakes are unlikely but highly impactful, ("low probability-high impact"), both the public and authorities often overlook preparedness, focusing more on post-event actions. Meanwhile, the scientific community advocates for mechanisms to raise risk awareness and drive mitigation efforts, countering prevailing complacency. Our focus will be on educational initiatives for all ages to enhance communication between experts and the public, complementing top-down strategies with a bottom-up approach. We will present several examples, emphasizing the need for political mechanisms to finance rehabilitation for low/middle-class communities, urban planning that considers all risks, and the role of citizen science.

## S12 Toward the next generation of earthquake ground-motions models, ShakeMaps and macroseismic scales

### AS25-0057

# Investigation of the ground amplification factor based on microtremor array observations at seismic observation points in Japan

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We have developed a shallow and deep integrated ground structure model for the Kanto region with the aim of evaluating broadband strong ground motions, and AVS30 and ground amplification factor (maximum velocity amplification factor) based on the developed ground model were released by the Earthquake Headquarters and J-SHIS in March 2021. The current evaluation of the ground amplification factor of surface ground in Japan has been carried out by Fujimoto and Midorikawa (2006), and the AVS30 used for ground amplification factor estimation is calculated based on PS logging results mainly from K-NET and KiK-net seismic sites of the NIED. However, at K-NET, boreholes deeper than 20 m have essentially not been carried out, and although KiK-net has PS logging at depths of more than 100 m, the accuracy of the surface ground is not high given the logging method. In this study, microtremor array surveys (small arrays) were conducted at about 1,750 K-NET and KiK-net stations throughout Japan, with the aim of verifying the accuracy of the ground amplification factor by AVS30 using a ground model, and to estimate the ground amplification factor accurately without PS logging, The objective is to evaluate the relationship between AVS30 and ground amplification factor based on the S-wave velocity structure obtained, to propose a new ground amplification factor, and to evaluate the optimum ground amplification factor if microtremor array observations are carried out.

## AS25-0100

# Regional site response model via Uncertainty Projected Mapping: Application to Kanto region, Japan

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Seismic risk assessment of critical infrastructure requires detailed site-specific investigation of local geological conditions. However, site-specific investigations at millions of spatially distributed assets – such as the Kanto region in Japan or the European Seismic Risk Model 2020 (ESRM20) – are impractical. A more practical approach for such regional scale risk assessments has been to use regional site-response maps. Such maps rely on site-specific ground-motion observations at a few well-characterized sites in the region, whose empirical site-responses are correlated to widely available 'proxy' parameters, e.g., topographic slope and geological era in ESRM20, and then used to predict site-responses at every location in the region. In some cases, geostatistical models (e.g., Kriging) are also used in combination with proxy parameters. Although such proxy-based regional site-response maps are quite practical, there are at least three issues: 1) Inefficient or insufficient proxies lead to incorrect site-response predictions, 2) Epistemic and aleatory uncertainties of predicted site-responses either do not correspond to site-specific data distribution or reflect the availability of site-specific observations and 3) Extrapolated and interpolated predictions are restricted by the imposed stationarity and isotropy of spatial correlation of observed site-responses. Proxy-based maps, with and without Kriging, share the last two issues. All three issues can be addressed using Uncertainty Projected Mapping (UPM). This study demonstrates the application of UPM to the Kanto region in Japan, evaluates its strengths and weaknesses against proxy-based and Kriging-based site-response maps, and discusses the potential of UPM as a tool for regional site-response mapping.

## AS25-0219

# High-frequency frontiers in site response and the added value of site-specific earthquake record-based measurements of velocity and attenuation

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One-dimensional ground response analyses based on 1D velocity profiles and generic relationships between damping and velocity are frequently employed with the assumption that they can provide a reliable assessment of site effects. According to this hypothesis, epistemic uncertainty in site response primarily stems from unconstrained soil properties, and this uncertainty rises sharply with increasing frequency in all Fourier-based ground-motion models. Our results show that the inversion of the spectral ratio of the horizontal-to-vertical components of strong motions based on the diffuse field concept accounting for the site-specific damping profile allows to capture significantly more site-specific features in site response, especially at high frequencies where both the deep sedimentary structure and the damping profile above the seismological bedrock have a strong influence on the disparity between observed and predicted ground motion. While the use of refined velocity and generic damping profiles for testing sites of the Japanese KiK-net already provides a reduction in the high-frequency residual and corrected site-to-site variability (and then the accuracy of predictions), the inclusion of site-specific damping allows this value almost to be halved. These results show that many sites are indeed too complex to be modelled by classical 1D ground-response analysis relying on generic damping relationships, while only site-specific record-based models allow a significant reduction in the bias with respect to coarse and generic site models.

## AS25-0419

# Developing VS30 Maps for Chinese mainland using VS30 measurements and secondary data constraints based on a large VS profile dataset

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Over the past three decades, extensive engineering projects in China have generated a vast amount of borehole-based shear-wave velocity (VS) measurements. To leverage these data for the development of China VS30 map, we compiled a comprehensive site profile dataset comprising tens of thousands of borehole profiles extracted from over 3,000 site investigation reports associated with engineering projects across Chinese mainland. This database is continuously expanding, with the addition of more than 1,500 borehole-based VS measurements from China strong-motion stations and over 600 from seismic stations located in hard-site in the Yunnan-Sichuan region.

In 2022, we proposed a Cokriging-based VS30 proxy model (SCK2022), which incorporates VS30 measurements as constraints and topographic slope as a secondary variable. This model produced the first VS30 map for Chinese mainland, constrained by 7,797 direct measurements. In 2024, we refined the SCK2022 model through algorithmic optimization (SCK2024). By integrating additional VS30 data from China strong-motion stations, we improved data coverage in western China, leading to a new version of VS30 map that fully covers Chinese mainland.

Our ongoing research aims to further enhance the SCK model by incorporating surface geology and depositional environment as additional parameters (GeoSCK). In developing the latest model, we addressed the issue of preferential sampling in VS30 measurements by applying a secondary-parameter-based debiasing method. The results indicate that the debiased site measurements more accurately capture the influence of geological parameters on site conditions.

## AS25-0483

# Towards Improved Magnitude and Ground-Motion Models for Switzerland: Insights from Consistent Datasets of Ground-Shaking Intensity Measures

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This study presents a dataset of ground-motion intensity measures (IMs) from 22,000 earthquakes recorded since 2000 in Switzerland and surrounding regions, compiled to support the development of new magnitude and ground-motion models. Initially, 2.6 million waveforms were processed, but a significant portion was eliminated based on strict quality criteria related to event and station metadata and signal-to-noise ratio. The final dataset includes IMs derived from 260,000 tri-axial waveforms with sufficient and homogeneous bandwidth and signal-to-noise ratio. To ensure consistency, all waveforms were processed using an automated workflow built on open-source seismological software. The processing workflow and associated software are publicly available to promote objectivity and reproducibility of the results. In addition to Wood-Anderson amplitudes, the dataset includes various other ground-motion IMs commonly used in engineering seismology, such as peak ground motions, response and Fourier spectra, and durations. Using the amplitudes in the dataset, station magnitude residuals are calculated for each waveform, and their behavior is investigated to identify the shortcomings of the current local magnitude model. The behavior of magnitude residuals highlights the need to account for near-source effects, complex path effects, and regionalization in the development of the future magnitude and ground-motion models in Switzerland and surrounding regions. Ongoing work to address the observed limitations of the current model, including advanced parameterization and integrating empirical data with physics-based numerical simulations, is also presented and discussed.

## AS25-0527

# Empirical site terms to improve the prediction of ground acceleration from Vrancea (Romania) intermediate-depth earthquakes

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During the past decades, the increase of the amount and quality of available strong motion records, as well as the increased complexity of the proposed empirical ground motion models, led to improved predictions of the median values of ground shaking at the sites. Nevertheless, the standard deviation of the residuals about the predicted median values – a key parameter in probabilistic seismic-hazard analyses – did not decrease significantly.

In recent years, the increased number of available ground motion records at single sites allowed to estimate the ground-motion variability without including the ergodic assumption, and the results show that single-station standard deviations are considerably lower than standard deviations admitting the ergodic assumption.

In the present study we consider the most recent ground motion prediction equation developed for Vrancea intermediate-depth earthquakes. Using a set of records from moderate-to-strong subcrustal events ($M_w$ in the range 4.5–7.4) well constrained regarding source parameters and site information, we calculate empirical site-specific terms for peak ground acceleration, and evaluate the potential for site corrections to reduce the aleatory uncertainty.

The site terms, defined as the average residuals from the prediction equation over the recorded earthquakes at each station, are included as predictive terms or adjustments to modify the median ergodic values.

By removing repeatable site-specific effects, the overall variability decreased by about 30%. This reduced aleatory variability, obtained under the nonergodic assumption, can be used in site-specific hazard calculations for the locations where the site terms and their epistemic uncertainty have been estimated.

## AS25-0642

# Distant attenuation of shear waves in the Netherlands

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Nearly 2000 induced events have been recorded on seismic stations of the Netherlands Seismic and Acoustic Network. For each recording, the maximum ground motion in the horizontal plane is extracted from the waveforms. This is expressed either in peak ground velocity (PGV) or peak ground acceleration (PGA). Using these PGVs and PGAs, detailed empirical ground motion prediction equations have been derived. These GMPEs predict the mean ground motion and their variability, as function of hypocentral distance and magnitude. Previously, these GMPEs were derived using data recorded at the surface and until approximately 40 km distance using data from especially the Groningen region. With further network expansions over the years, there are also many recordings available at larger distances and for other regions. Recently, we compiled a database with more than 30 000 ground motions extracted from recordings made at 200 m depth. The advantage of using recordings at depth is that they have a limited imprint of site conditions. Moreover, due to the lower noise conditions, more ground motions can be extracted at larger distances than at the surface. We derive GMPEs that have an empirical base until 110 km hypocentral distance. At distances beyond 40 km there is interaction of crustal and mantle phases. This leads to jumps in the attenuation as a function of distance, related to the appearance and disappearance of phases. We show this complex attenuation at larger distances and discuss the underlying wave-propagation characteristics using numerical modeling.

## AS25-0664

# Influences of Soil Nonlinearity on Pulse-Like Ground-Motion Simulated by a Stochastic Finite-Fault Derived Method for the 2023 Turkiye Mainshock

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During the 2023 Mw 7.8 Türkiye earthquake, over 25 pulse-like velocities (VP) were observed in the near-fault area. Significant differences in VP intensity were noted at three stations within a 3 km near-fault zone, particularly at Antakya, a major disaster region, which recorded the second-largest peak ground velocity (PGV) among all VPs measured. The PGV and Tp values varied by two to three times across the three stations. This study began by removing the coseismic static offset to mitigate one-sided pulse motion effects through baseline correction and fling-step removal. Next, we simulated the directivity pulse with a velocity-pulse simulation procedure (Huang et al., 2024). We utilized the stochastic finite-fault ground-motion simulation (GMS) approach, integrated with linear site response based on the empirical transfer function method. We also identified significant soil nonlinearity using the short-time Fourier transform for the horizontal-to-vertical spectral ratio at the largest PGV station, 3123. A proxy for shear modulus reduction, fsp, proposed by Castro-Cruz et al. (2020), was applied to the GMS, confirming that the Tp shifted from a linear 3.5 s to a nonlinear 2.6 s. These findings show that the directivity pulse resulted in an approximate PGV of 60 cm/s, which doubled due to the linear site response. The threefold PGV recorded at station 3123 is attributed to linear site response and super shear behavior in the near-source region, with soil nonlinearity responsible for the Tp shift, observed as a final observation.

## AS25-0707

# Ground motions and macroseismic intensities in Groningen, the Netherlands

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Apart from instrumented ground motions, the seismological agency KNMI in the Netherlands also collects earthquake experiences from the public through online inquiry forms. We have analysed the inquiry forms for the induced earthquakes from the Groningen gas field with a maximum local magnitude of 3.4. There were two versions of the inquiry forms. After 2015 the questions and answers were based on the international standard. These forms could easily be transformed to macroseismic intensities. The macroseismic intensities were then coupled to ground motions from ShakeMaps for earthquakes with magnitudes larger than 2.0. The scatter in datapoints is quite large, but the general trend of larger macroseismic intensities for larger ground-motion levels is apparent. An invertible relation between the ground motions and the macroseismic intensities was derived by orthogonal regression. Our relation shows a steeper gradient for macroseismic intensity as a function of PGV or PGA relative to worldwide relations. This is partially due to the limited magnitude range in our data set. The inquiry forms from 2008 to 2015 were based on a different set of questions and answers. They first need to be converted to the international standard set before macroseismic intensities can be calculated. If this conversion can be done unambiguously, our data set would grow with a factor of 4.

## AS25-0712

# Simulating ground motion from the 1992, MW=5.3 Roermond (The Netherlands) earthquake using EGF and EXSIM

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The MW=5.3 1992 Roermond earthquake remains the largest instrumentally recorded (and damaging) earthquake in NW Europe, and thus a key reference event for ground-motion modelling and seismic hazard assessment in this region. However, despite numerous seismometers in the vicinity of the event, ground motions at R < 100 km remain largely unknown due to record clipping. In recent years, computational power and methods have significantly advanced. Examples include the ability to model ground motions based on finite fault sources, using empirical Greens' functions (EGF) or stochastic simulation (EXSIM), including probabilistic uncertainty quantification. These methods are based on discretization of a fault rupture into subfaults, followed by time-delayed summation of accelerograms associated with each. In EGF, the subfault accelerograms correspond to a recorded small-magnitude aftershock, while in EXSIM, they are stochastically simulated for each subfault with a dynamic corner frequency. An advantage of EGF is that the aftershock record already includes the path and site attenuation effects, while these are estimated in EXSIM. Conversely, EXSIM can easily account for random variation because accelerograms are independently simulated for each fault. By exploring the differences between both methods, we correct aftershock records used in EGF such that the same spectral scaling factors as in EXSIM can be applied. We tested these methods for the closest station where the mainshock was recorded intactly, obtaining good agreement with observed ground motions. Further work aims to leverage both methods to reconstruct mainshock epicentral records, which will lead to a reference dataset, including uncertainty.

## AS25-0721

# Uncertainty Quantification in Kinematic Rupture Models Using Stochastic Slip Distributions for Tsunamigenic Earthquakes

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Large tsunamigenic earthquakes are devasting events that cause significant casualties and damage. Understanding their rupture characteristics remains challenging due to their inherent complexity, variability, and scarcity of observations. In this context, numerical simulations are crucial in bridging gaps between observational data and enhancing our ability to simulate the rupture dynamics in large earthquakes and their associated ground motions. In this study, we evaluate the epistemic uncertainties in ground motion predictions using a kinematic rupture method based on a heterogeneous stochastic slip distribution for large tsunamigenic earthquakes (Crempien et al., 2020). We generate earthquake scenarios from magnitudes (Mw) in a range of 8.1 to 8.5, simulating the Illapel Mw 8.3 Earthquake in Central Chile. Additionally, we estimate ground motion associated with these scenarios using numerical Green functions and compare them with real observations from strong-motion near-field stations. Key parameters are analysed, including the probability distribution of peak ground displacement, pulses, spectral content and waveform similarity. This assessment aims to quantify the uncertainties of this rupture method, providing valuable insights for hazard analysis. Our results are expected to be used in a full physics-based seismic tsunami hazard assessment in Central Chile.

## AS25-0811

# Accounting for structural effects in ground motion estimates via ShakeMap

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ShakeMap provides rapid site-specific ground motion intensity estimation in the area struck by an earthquake. It is typically used for rapid response; nevertheless, several applications use the ShakeMap estimates for earthquake engineering and engineering seismology research, such as observational structural fragility estimation. The current procedure to develop a ShakeMap rests on the assumption of a Gaussian random field (GRF) for the logs of ground motion intensities conditional on earthquake magnitude, location and, typically a few, shaking recordings from seismic monitoring stations. On the other hand, a series of other earthquake effects are measured after a major event, most notably damages to buildings. Recent literature shows that, in the case a fragility model is available for the damage-surveyed buildings, each structure can be used to probabilistically infer the ground motion that cause such damage, even if no recording is available at the construction site, which therefore can be – in turn – used as a further conditioning information to the ShakeMap. This study shows that, in the case of urbanized areas, the information brought by damage can lead to change the ground motion picture for a past event, with respect to the ShakeMap one neglecting damage information. More specifically, either the site-specific median estimation and its uncertainty may be affected, especially at and around the damage-surveyed sites. These issues are illustrated referring to the case study of the 2009 L'Aquila (central Italy) earthquake, also considering the possible uncertain damage attribution by surveyors.

## AS25-0843

# Site-specific ground motion model using partially non-ergodic neural network approach, for the area of Greece

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We present a new region-specific ground motion model (*GMM*) for the area of Greece. Using a data-driven approach, we avoid considering any a priori functional form. Due to the limitations of recent Greek datasets, selected records from the RESORCE database were also integrated. A fully connected multilayer perceptron neural network is used to predict ground motion intensity measures (*GMIMs*), such as peak ground velocity (*PGV*), peak ground acceleration (*PGA*), and 5% damped pseudo-spectral acceleration (*PSA*) at 18 oscillator periods ranging from 0.01 to 4.00 s, for shallow active crustal earthquakes (≤ 30 km). The proposed *GMM* model relates GMIM predictions to three input parameters: moment magnitude ($M_w$), Joyner-Boore distance ($R_JB$), and average seismic shear wave velocity in the uppermost 30 meters of the site ($V_{S30}$). The linear mixed effects algorithm (Bates et al., 2015) is used to decompose the random components into inter-event residuals ($\delta B_e$) and site-to-site residuals ($\delta S2S_s$), while imposing the heteroskedasticity assumption to analyze the dependencies between the random ground motion variability (*GMAV*) components and the predictive parameters. The sensitivity of the input parameters for model prediction is also analyzed. The results indicate that combining the partially non-ergodic assumption ($\delta S2S$) with the heteroscedastic model significantly reduces *GMAV*, while these data-driven predictions show physical trends consistent with conventional *GMMs*. This new site-specific *GMM* takes into account the spatial variability of ground motion across Greece.

## AS25-0865

# Towards the Development of Static Ground Displacement and Transient Ground Strain ShakeMaps

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We are working towards two new tools to complement the U.S. Geological Survey ShakeMap product suite, namely (1) static ground displacement (SGD) and (2) transient ground strain (TGS). Damage to shallow, buried structures and lifelines can be caused both by dynamic strains (primarily axial strains) and permanent deformation (including broad uplift, localized faulting, or ground failure). Detailed SGD and TGS maps will greatly improve the characterization of both causes. SGD maps require vector displacement representation, static deformation predictions rather than response spectral estimates, and geodetic observations. TGS ShakeMaps require strain calculations, often approximated as $e=PGV/C$, where $PGV$ is peak ground velocity, and $C$ is a site's shear velocity; yet, rigorous strain calculations require setting $C$ to the *phase velocity.* Calibration with three-dimensional earth and rupture models will aid in analyses, but real-time waveform analyses are needed to determine whether body- or surface waves are responsible for the TGS. TGS ShakeMaps will require conditioning on TGS observations, including strainmeters, seismic arrays, and distributed acoustic sensing. Projecting radial strain to the pipeline orientation is required, and we can do that within ShakeCast, which considers impacts on pipelines with known orientations. This work's initial calibration phases will provide valuable insight into the ground motion conditions that dominate the relative effects of SGD vs TGS, which have not been well-characterized in the literature to date. Our new analyses and ShakeMaps will facilitate the development of better pipeline fragilities and will ultimately be extremely useful to lifeline utilities, among others, for planning and response.

## AS25-0867

# Developing And Implementing an International Macroseismic Scale (IMS) For Earthquake Engineering, Earthquake Science, and Rapid Damage Assessment

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Macroseismology plays a crucial role in earthquake hazard and risk analyses, tying earthquake occurrences and impacts from the past with those of the present and future. Nonetheless, even with best practices, there are critical limitations to many modern macroseismic data collection approaches. For example, the United States and New Zealand still employ intensities based on variations of the Modified Mercalli Intensity (MMI) scale, consistent with—but inferior to—the more recently developed 1998 European Macroseismic Scale (EMS-98). Practitioners in many other countries outside of Europe deploy EMS-98 formally or informally, and elsewhere, a wide variety of macroseismic scales are in use, complicating consistent analyses worldwide. We report on our efforts to develop an International Macroseismic Scale (IMS), building on the EMS-98 framework. We motivate the IMS, noting its seismological and earthquake engineering benefits and summarize the historical efforts leading to this global scale. We then describe key features of the IMS, its consistency, and differences with respect to the EMS-98 framework, including additional structures in an expanded building vulnerability table and the deemphasis on ground failure as an indicator of shaking intensity. Moreover, the IMS allows for national annexes that document crucial structural characteristics, code era, compliance, and other potential vulnerability modifiers specific to various countries and regions to help narrow vulnerability class assignments. We also report on and solicit input from national macroseismic practitioners to characterize macroseismic practices and promote IMS use worldwide. To this end, we hope to form an IASPEI-hosted IMS-25 Working Group at this conference.

## AS25-0891

# Enhancing ShakeMaps in urban areas using accelerometric measurements from citizens' smartphones

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Over the past 10 years, smartphone technology has been a game changer in earthquake early warning (EEW), making it possible to detect seismic events in real time and alert people in areas not covered by traditional warning systems. The potential of smartphone ubiquity, however, is not limited to EEW. In this work, we show how spatially dense accelerometric smartphone measurements are used to improve ShakeMaps in urban areas, where the improvement is most needed to accurately assess the impact of earthquakes. Our methodology is based on a statistical data fusion model that naturally handles the different characteristics of station and smartphone data, and does not require smartphone data to be calibrated against high quality reference measurements. The methodology is applied to generate high spatial resolution (uncertainty included) ShakeMaps in the Campi Flegrei area, Italy, using station peak ground accelerations and smartphone measurements collected by the Earthquake Network citizen science initiative, the first public smartphone-based EEW system.

## AS25-0893

# Reproduction study of transfer function from vertical array observation with two-dimensional optimal S-wave velocity structure model

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A soil amplification is often considered based on a one-dimensional (1D) ground response analysis with a horizontally layered S-wave velocity structure for evaluating an earthquake ground motion. It is important to use the appropriate 1D model that well reproduces observed ground motions. However, in areas having significant irregularity of S-wave velocity structure, the approximation of the velocity structure as horizontally layered might not be appropriate. In this study, we developed a method to evaluate a two-dimensional (2D) S-wave velocity structure model by an inversion with earthquake ground motion records at a vertical array observatory, and performed a case study on KiK-net station of Kamaishi, Japan.

The station is located in the Kitakami Valley, and the S-wave velocity structure in the surrounding area is complicated. A transfer function from GL-103 m to GL has a characteristic peak with the maximum amplitude at a frequency of 16 Hz. This peak cannot be reproduced with the 1D analysis.

In our method for the 2D model, the depth distribution of the S-wave velocity boundary around the observatory and an attenuation are estimated by the inversion with the coincidence ratio between the observed and 2D synthetic transfer functions. We demonstrated that a stable solution with few trade-off relationships among unknown parameters could be obtained by using the S-wave velocity structures by PS logging and a microtremor array exploration performed around the observatory as constraints, and that the reproducibility of the observed amplitude at a frequency of 16 Hz is significantly improved compared to the conventional 1D analysis.

## AS25-0914

# Examination of S-Wave radiation characteristics in the 2021 and 2022 Off-Fukushima earthquakes for improving ground motion prediction models

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Currently, most empirical ground motion prediction models use RMS amplitude without considering directional differences. However, previous studies on inland crustal earthquakes have demonstrated a four-quadrant radiation pattern at low frequencies. These inland crustal earthquakes were mainly strike-slip earthquakes. On the other hand, many reverse-fault earthquakes occur around subduction zones. M7-class earthquakes occurred off Fukushima, Japan on February 13, 2021 (Mw 7.1, depth 55 km) and March 16, 2022 (Mw 7.4, depth 57 km). We aimed to estimate the radiation characteristics for these reverse-fault earthquakes.

We analyze the S-wave horizontal motion for the 2021 and 2022 events, which were intraslab events. For station FKS003, the peak accelerations of both components were similar values, but the peak velocity of the Radial (R)component (28 cm/s) was twice that of the Transverse (T) component (14 cm/s). The Fourier spectrum in the low-frequency range (<1 Hz) showed that the R component was 2–3 times larger than the T component, while in the high-frequency range (>10 Hz), both were similar values.

Spatially, the amplitude ratio (AT) showed a bias in the low-frequency range (<2 Hz), but no distinct pattern was observed at higher frequencies (>3 Hz). The AT between the T and R components was compared with theoretical values. Correlation analysis revealed that the S-wave radiation pattern was attenuated at high frequencies (>6 Hz) and long distances (>300 km), likely due to wave scattering. Future studies will investigate other earthquakes around the Japan Trench and the South Kuril Trench to explore these characteristics further.

## AS25-0934

# The Greek Earthquake Impact Database (GEIDB): AD 1800–2024

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Earthquakes affect societies causing a variety of effects in both the built and the natural environments. The area of Greece is characterized by the highest seismicity in the western Eurasia with historical documentation of earthquakes since the 5th century BC. Observational material relevant to historical and instrumental earthquakes and their impact in Greece can be found in several information sources including descriptive and parametric earthquake catalogues, specific papers, books, reports, pictorial material and other documents. Some international databases contain only sporadic and often inaccurate information about the impact of Greek earthquakes. We organized for the first time the Greek Earthquake Impact Database (GEIDB), which covers the time interval from AD 1800 to 2024 and includes building damage data, fatality and injuries rates as well as data regarding secondary earthquakes effects, such as tsunamis and ground failures, e.g. surface fault traces or fissures, soil liquefaction and landslides. These elements have been compiled from several information sources and were included in the GEIDB after a procedure of reliability filtering, correction and data adoption or rejection based on cross-checking of information sources. Apart from earthquake impact data, the GEIDB includes also parametric data regarding the earthquake focal parameters (origin time, epicenter, focal depth, magnitude) and macroseismic intensity assignments. Only synoptic tsunami data are included in the GEIDB since detailed information is contained in a separate Greek Tsunami Impact Database (GTIDB). An extension of the GEIDB before the reference period of 1800–2024 is in progress.

## AS25-0988

# Empirical characterization of near-field ground motion pulses: A comparison of the 2022 Düzce and 2023 Kahramanmaras Earthquakes with physics-based simulations

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Turkey is marked by two major fault systems, both of which frequently generate moderate and large magnitude earthquakes and cross densely populated cities, namely the North-(NAF) and East Anatolian Faults (EAF). In 2022, the NAF ruptured in a Mw 6.1 earthquake close to Düzce and highlighted the role of near-field ground motion effects, while generating severe seismic damage on surrounding buildings (>600). Most recently in 2023, the EAF ruptured in two large Mw 7.8 and Mw 7.5 earthquakes (2023 Kahramanmaras seismic sequence), which caused widespread damage far beyond near-fault area and cost more than 55,000 lives. In both cases, we analyze the AFAD-Turkish Accelerometric Database and investigate occurrence of pulse-like ground motions, indicating also directivity effects. Further, we characterize ground motion velocity pulses with observed and synthetic waveforms against 3D dynamic rupture simulations. For the moderate, 2022 Düzce earthquake, our findings suggest that impulsive ground motions, typically linked to directivity effects, may occur also on the fault-parallel component in given near-fault regions, challenging existing literature. The 2023 Kahramanmaras sequence shows significant variability in pulse properties in near-fault regions, which were not fully captured by the physic-based simulations. Our findings highlight the importance of analyzing pulse characteristics, even for moderate earthquakes, to get a better understanding of the correlation of pulse- and physical rupture properties. Additionally, our results emphasize the need for development of rupture simulations, capable of accurately reproducing these properties.

## AS25-1004

# Towards the development of the next-generation stochastic model for Switzerland: Integrating New Data, Models and Advanced Methodologies

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We aim to update the existing stochastic model for Switzerland (Edwards and Fäh, 2013) by leveraging an additional decade of data from a larger number of stations, coupled with the recent advancements in ground motion modeling. We initiated our update by focusing on the two key aspects of the stochastic modelling—ground motion duration and path attenuation. Specifically, we have adapted the widely used duration model by Afshari and Stewart (2016) to the seismological conditions in Switzerland, focusing on 2xT20–80 for stochastic simulations suited to Switzerland's low to moderate seismicity. We applied a distance-dependent update to the duration model, and the revised model demonstrated improved performance for Swiss data, with the mean residuals shifting closer to the zero baseline. After updating the model for consistency with Swiss data, additional modifications were made to tailor it for stochastic simulations using SMSIM. Next, we focused on the path attenuation component of the stochastic model. Our analysis showed that for very shallow events, the current model overpredicts due to its assumption of a uniform quality factor and S-wave velocity across Switzerland. We investigated the depth-dependent variations in path attenuation and the results indicate that shallow seismic events attenuate more rapidly than deeper ones. To address this issue, we have decided to integrate the recently developed Swiss 3D velocity and quality factor models into the forthcoming stochastic model for Switzerland to enhance its accuracy and reliability.

## AS25-1064

# Investigating Fault Parameters and Site Effects Through Physics-Based Ground Motion Simulations

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The objective of this study is to analyze the impact of fault parameters on ground motion simulations in the Mugello region of Florence, Italy. The area includes a sedimentary basin several hundred meters thick, bounded by two normal fault systems. Three-dimensional (3D) numerical modeling of seismic ground motion is performed, accounting for the complexity of source rupture and wave propagation within the basin. A sensitivity study with multiple rupture scenarios is conducted by investigating the physical parameters of the fault model, focusing on fault geometry, fault position, and kinematic parameters such as slip distribution, rupture velocity, and hypocenter location relative to fault asperities, which controls directivity effects.

These parametric analyses are carried out in the context of simulating historical earthquake ground motions. To evaluate the validity of the simulated scenarios, peak ground velocity (PGV) values obtained from numerical simulations are compared to the those inferred from the reported macroseismic intensity fields. The full simulation of the 1542 (M 6) and 1919 (M 6.3) earthquake scenarios will be performed. Future work will also include testing these simulated ground motions on historical structures such as bell towers, for which damage has been reported.

## AS25-1083

# A Comparative Study of Boosting Algorithms and Optimization Techniques for Ground Motion Modeling in Turkiye

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This study investigates the performance of various boosting algorithms in predicting peak ground velocity (PGV) and cumulative absolute velocity (CAV) of strong ground motions. Building upon the authors' previous work, in which multiple machine learning (ML) algorithms were evaluated to identify the most suitable ML-based ground motion model (GMM) for Türkiye, Gradient Boosting was found to provide the most accurate predictions for PGV and CAV. Accordingly, this study further examines the predictive capabilities of boosting algorithms in detail. Gradient Boosting, CatBoost, Natural Gradient Boosting, Light Gradient Boosting Machine (LightGBM), and XGBoost algorithms are employed to develop Türkiye-specific GMMs for PGV and CAV using an extended dataset. In the second part of the study, hyperparameter optimization is performed using GridSearchCV and Particle Swarm Optimization (PSO) techniques. The models are trained on the Turkish Strong Motion Database, which comprises records from over 950 earthquakes that occurred between 1983 and 2023. Key source, path, and site characteristics are included as predictor variables in model development. The performance of the models is assessed using statistical performance metrics as well as analyses of inter-event and intra-event residuals. The findings indicate that, in the first phase, the CatBoost algorithm outperforms the other boosting algorithms in predicting both PGV and CAV. In the second phase, the CatBoost-PSO model demonstrates superior predictive performance, achieving high precision and reliability. In particular, the CatBoost-PSO model provides predictions for PGV and CAV that are comparable to, or better than, existing ML-based and traditional prediction models.

## AS25-1089

# Assignment of Macroseismic Intensity Values in the Field after the 6 February 2023 Kahramanmaraş (Turkey) Earthquake Sequence

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Evaluating macroseismic intensity is crucial after significant earthquakes to determine the impact and severity of the seismic events. While traditional on-site intensity assessments tend to be more localized and subjective compared to internet-based methods like questionnaires, they remain important for understanding the scope of earthquake-induced damage. In Turkey, the Modified Mercalli Intensity (MMI) scale continues to be the primary tool used for rapid post-earthquake evaluations to guide emergency response efforts. This study examines the damage to structural, geotechnical, and lifeline systems in the vast area affected by the February 6, 2023, Kahramanmaraş earthquake sequence, considering factors like source-to-site distances, local site conditions, and ground motion levels. The MMI map derived from field observations is then compared with DYFI maps and digital maps generated through ground motion-to-intensity conversion equations. Additionally, we explore the challenges and uncertainties associated with assigning micro-seismic intensity, along with potential solutions. Such initiatives can enhance response prioritization, improve resource allocation, and inform future preparedness and mitigation strategies.

## AS25-1145

# Ground Motion Models for Low-Magnitude, Shallow Seismic Events: Analysis using seismicity recorded in the Val D'Agri area, Southern Italy

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Ground motion models (GMM) are mathematical models used to estimate earthquake ground motions. These models are essential in seismic hazard assessments and earthquake engineering, and due to this kind of applications, GMM are mostly developed for predicting ground motions using data from large events. However, in recent years the interest in the effects of relatively low-magnitude, shallow seismicity (as e.g., seismicity observed in volcanic areas or seismicity induced by anthropogenic underground operations), has increased; such kind of seismic events are smaller in scale, and given the relatively shallow location, high frequencies and near source effects could be more prominent. As a consequence, traditional GMMs developed for larger earthquakes may not accurately scale down to micro-seismic levels. The objective of this work is to study ground motions caused by relatively small, shallow, seismicity recorded in the Val D'Agri area, Southern Italy. We implemented a Markov Chain Monte Carlo (MCMC) approach for model parameter estimation, testing different functional forms to select the one providing the best fit to observations. Finally, we use the selected model to forecast ground motions taking into account the uncertainties of the model parameter values. The results presented in this study highlight the importance of capturing the uncertainties in model parameter estimation and of propagating such uncertainties in the forecasting of ground motions. Moreover, using an independent dataset of observations, we test the performance of the obtained model; further developments focused on including local site conditions may reduce the misfit between observations and forecasts

## AS25-1146

# Updated ground-motion intensity conversion equations for the Western United States

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Using a new data set for macro intensity from crustal earthquakes in the Western United States (WUS), a new ground-motion intensity conversion equation (GMICE) is developed. The data set includes 54,900 intensity observations within 3 km of a ground motion observation from 614 earthquakes with magnitudes between 3 and 7.5. The standard approach for developing GMICE assumes that the intensity depends on the ground-motion amplitude, independent of the magnitude and distance. This simple form is convenient for applications of GMICE; however, it is not consistent with the observations. The magnitude and distance scaling in a ground-motion model and in an intensity prediction equation were used to evaluate the scaling between intensity and ground motion for given scenarios. There is a strong magnitude dependence in the relation between intensity and peak ground velocity (PGV) with small-magnitude earthquakes leading to a larger intensity than large-magnitude earthquakes for the same PGV. This behavior is also seen in a direct evaluation of the scaling of the GMICE. In the magnitude-dependent GMICE, the slope of the ln(PGV) is dependent on magnitude with steeper slopes for larger magnitudes and there is saturation for large PGV values. For example, the upper limits on the median intensity are 4, 6, and 9 for M=3, M5, and M7, respectively. Including a magnitude dependence complicates the application of the GMICE, but this dependence is needed for the GMICE to scale appropriately. A simplified GMICE without a magnitude dependence is also developed but it has much larger aleatory variability.

## AS25-1177

# Incorporating HSIT data into ShakeMap: a comparative analysis

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This study explores the impact of integrating data from Hai Sentito Il Terremoto (HSIT, https://www.hsit.it/)—a well-established citizen science initiative that collects reports and provides real-time feedback on earthquake effects using the Mercalli-Cancani-Sieberg (MCS) and European Macroseismic Scale (EMS)—into the intensity shaking maps generated by the ShakeMap service of the Istituto Nazionale di Geofisica e Vulcanologia (INGV, https://shakemap.ingv.it/).

The analysis focuses on past earthquakes across Italy, covering events of varying magnitudes, station coverage, depths, and locations. Five ground motion parameters— Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Spectral Acceleration (SA) at 0.3s, 1.0s, and 3.0s— along with intensity, were examined. Our methodology followed three key steps. First, we assessed the consistency between HSIT data and the Ground Motion to Intensity Conversion Equation (GMICE) used in ShakeMap, evaluating their reliability within this established framework. Next, we analysed the influence of HSIT data on ShakeMap results by comparing intensity maps generated with and without their inclusion, conducting separate analyses for the MCS and EMS scales. Finally, we recalculated a representative subset of intensity shaking maps available on shakemap.ingv.it from 2021 onward, producing two configurations—one incorporating HSIT data and one excluding it. This allowed us to quantify the differences between the two sets of shakemaps, identify potential patterns, and evaluate the intensity ranges and distances where HSIT data enhance the accuracy of ground shaking estimates. This comprehensive assessment provides insights into how citizen-reported data modify ShakeMap outputs, particularly in regions with diverse seismic conditions and varying data availability.

## AS25-1200

# Updating Shakemap for Italy: selection of ground motion models for volcanic areas and cumulative mapping tools for civil protection

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The recent seismic activity in the Italian volcanic areas, particularly the intensification of bradyseism in the Phlegraean Fields, highlights the need to update seismic motion analysis tools. This study presents the enhancement of the ShakeMap system for Italy by implementing new Ground Motion Models (GMMs) specifically designed for volcanic zones. These models account for the unique geological and dynamic characteristics of these regions, providing more accurate estimates of ground shaking intensity. In particular, the seismicity in some volcanic areas, such as Mt. Etna and the Phlegraean Fields, presents a peculiar scenario where relatively small but shallow earthquakes can cause significant local damage. Therefore, this research focuses on near-epicentral observations to evaluate the ability of the selected GMMs to predict ground shaking in the near-source region of shallow events. The assessment of the available GMMs is made through the adoption of cross-validation techniques. In addition, a new tool has been developed to produce "cumulative" maps of ground-shaking that take the maximum values of the peak ground motion parameters for a given region and time period. These maps appear crucial for civil protection strategies (e.g., disaster risk management) and long-term risk assessments. By serving as a benchmark for comparing observed shaking levels with predictions from seismic hazard models, they improve the understanding of seismic impact and risk distribution. The results demonstrate significant improvements in ShakeMap's ability to capture the seismic features of volcanic areas and provide a robust foundation for enhancing the resilience of Italian territories to seismic and volcanic risks.

## AS25-1232

# Towards a data-driven approach for empirical fragility assessment: Application to Kahramanmaraş Türkiye Earthquake 2023

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In current practice, empirical fragility curves are developed for each class of buildings separately based on the pairs of seismic ground-shaking intensity (*IM*) and physical damage observations gathered from spatially distributed buildings. We propose a Bayesian data-driven workflow to account explicitly for the uncertainties in the *IM* estimation at building sites through application of ground-motion models (GMMs) for the earthquake of interest and the corresponding spatial correlation structure. The workflow further considers the hierarchical dependencies between damage levels, the uncertainty in the fragility parameters, and correlations in fragility parameters for different classes of buildings. This is made possible through a simulation-based Bayesian workflow that uses adaptive importance sampling technique. For the input data, the workflow employs both the registered *IM*s at nearby seismic stations and the observed damages. Given an earthquake event, random fields of *IM*s are generated to derive plausible empirical fragility curves for different damage states of all the building classes. We apply the workflow to derive fragility curves and their $16^{th}$–$84^{th}$ percentiles for 13 building classes and 3 mutually exclusive and collectively exhaustive damage states as an ensemble based on generated *IM*s and observed damages from the 6 February 2023 Kahramanmaraş Türkiye Earthquake. The generated empirical fragility curves show reasonable agreement with the recently developed empirical fragility curves for Türkiye, and with the analytical fragility curves based on the European Seismic Risk Model (ESRM20) for similar taxonomies. Moreover, we verify the generated ground shaking field with its uncertainty with the observed station data within the survey area.

## AS25-1235

# Development of Backbone Ground-Motion Models for the 2024 Earthquake Model of the Middle East (EMME24)

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In this contribution, we present a framework for developing parametric backbone ground-motion models (GMMs) tailored for active shallow crustal seismicity within the 2024 Earthquake Model of the Middle East (EMME24).

In EMME14, epistemic uncertainty in ground motion was represented using a multiple-GMM approach, based on data-driven model selection and logic-tree weighting. However, recent advances in ground-motion modeling have shown that this method has limitations in fully capturing epistemic uncertainties. To address these challenges, alternative approaches such as backbone modeling have gained recognition. In this framework, a specific GMM is selected as the center model and then systematically scaled to account for the full range of epistemic uncertainty in ground-motion amplitudes for various magnitude and distance scenarios.

We describe the characteristics of the developed backbone GMMs, and compare epistemic uncertainty estimates between the multiple-GMM and backbone-GMM approaches at selected sites. These models are applied to compute regional ground shaking, represented by spectral acceleration up to 10 seconds, for a generic rock site class. Additionally, we assess how this framework influences ground-motion estimates across the region.

## AS25-1240

# Rapid, non-ergodic, empirical shaking scenarios in Italy

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The aim of this study is to produce rapid, non-ergodic, empirical ground shaking scenarios at the site that account for the regionalization of source, attenuation and site effects in Italy. The selected Ground Motion Model for Italy, Lanzano et al (2019), is adjusted locally to take into account the region-specific source, attenuation and site effects.

Source and attenuation correction factors are calculated through a residual analysis approach, e.g. based on the difference between the logarithm of observed and predicted intensity measures, that allows to define the spatial distribution of zones with homogeneous source effects and anelastic attenuation (Brunelli et al., 2023). Site effects are taken into account by a linear dependence on the logarithm of the shear wave velocity in the uppermost 30 m (Vs30), whose spatial distribution is evaluated by relating observed Vs30 and a series of proxies (lithology and topography).

The shaking scenarios are calculated in terms of peak ground acceleration and velocity (PGA, PGV) and acceleration response spectra ordinates (5% damping) for the horizontal components.

## AS25-1241

# Towards a common understanding of macroseismic and instrumental information: 25 years of IPMA experience with EMS-98

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Since the beginning of the 21st century, various tools and systems have been integrated into the routines and procedures of IPMA`s seismic monitoring in Portuguese territory, adapted to local conditions. Notably, the European Macroseismic Scale (EMS-98) and ShakeMap (USGS) have been prominently applied.

With the widespread accessibility of the Internet, tools like "Did You Feel It?" (USGS) have been specifically designed and made available to IPMA users. Additionally, algorithms have been developed to analyze data from online macroseismic questionnaires.

Recent seismic events on August 26, 2024 and February 17, 2025, felt by a significant portion of the Portuguese mainland population, have provided a substantial amount of macroseismic intensity data. These can be compared with instrumental data from the national seismic network stations, particularly peak ground acceleration (PGA) and velocity (PGV) values. This comparison will contribute to calibrate intensity assessment in zones of higher uncertainties, improving seismic intensity attenuation curves, especially for the near-field events.

The analysis of data collected over the years has enabled the development of a more structured perspective on the use of tools like EMS-98. Now, with conditions allowing for a comprehensive evaluation of this scale after more than a quarter-century of increasingly widespread global application, we highlight some key considerations that may be useful at this stage, the main one being the need for a new version of the scale to incorporate a chapter dedicated to algorithmization, with proposals, examples and ways to harmonize its application among the various national agencies.

## AS25-1242

# Establishing the Transition Long Period Map of the Philippines

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The National Structural Code of the Philippines is set to be updated to align with the National Structural Code of the Philippines is set to be updated to align with international standards by incorporating the American Society of Civil Engineers' ASCE 7–05, specifically its Minimum Design Loads and Associated Criteria for Buildings and Other Structures. This update introduces the Transition Long Period (TL) parameter, which aims to provide accurate representations of ground motion for periods exceeding 4 seconds, significantly impacting the design of long-period structures. To determine TL values for the Philippines, data from the Seismic Hazard Assessment for Design Earthquake (SHADE) Project, conducted by DOST-PHIVOLCS, were used. This involved preparing maps of modal magnitudes (Md) through the disaggregation of the 2% in 50-year hazard for spectral acceleration at T=2 seconds, which were then correlated with corresponding corner period values (TC). Seismic sources were categorized into fault, subduction, and area sources. The resulting TL map for the Philippines shows values ranging from 4 to 16, with intervals of 2. The findings indicate that in regions adjacent to fault sources, the magnitudes predominantly originate from the fault itself, whereas in other areas, the magnitudes are influenced by subduction sources.

## AS25-1248

# Can we quickly calculate reliable earthquake parameters from citizen testimonies?

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In a recent work, we tested the ability to compute macroseismic parameters (location and magnitude) using citizen testimonies collected by the European-Mediterranean Seismological Centre (EMSC), via LastQuake system. Each IDP is archived by EMSC with the time delay from the earthquake origin time. To use IDPs as classic intensities, i.e. macroseismic data points (MDPs), representing damage at an urban scale, they must be grouped into spatial clusters, which are then processed by the BOXER code to locate and size earthquakes. A retrospective analysis on a dataset of more than 15,000 events collected over the past 10 years shows that the procedure can provide reliable parameters and that the results depend on the geographical area and improve over time and as the number of available IDPs/MDPs increases.

The key question is whether early IDPs/MDPs can quickly provide reliable parameters (location and magnitude) for users and stakeholders (e.g. the civil protection agencies). Using clustering methods that statistically provide, on average, the best agreement with instrumental data, we tested some predefined time intervals within which to group the available IDPs into MDPs. We then applied the BOXER code to these MDPs, evaluating the agreement with the final instrumental parameters. Results confirm that reliability increases with the number and distribution of MDPs, strictly dependent on the number and distribution of available IDPs. This retrospective analysis demonstrates the effectiveness of the approach and its potential to quickly provide parameters for future real-time applications.

## AS25-1270

# Machine learning for automatic integration of macroseismic data—from testimonies to EMS98 intensities

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A large macro-seismic database have been built up from years by the the French Central Seismological Office and the National Seismic Monitoring Network (BCSF-Rénass), compiling individual and communal testimonies as well as field data, and collected through the BCSF-Rénass website (https://www.franceseisme.fr; https://renass.unistra.fr) and during macro-seismic missions carried out by the GIM. This database has recently been carefully sorted, cleaned and structured by analysts, and represents a high-quality data set that is perfectly suited to the development and use of supervised machine-learning algorithms. By way of example, nearly 10,000 individual forms have been collected in 2021, and over 100,000 communal intensities estimated since the last century. It is still a major challenge to connect macroseismic information to seismic intensities and to instrumental measurement. Here we present results of a machine learning algorithm trained on the BCSF-Rénass consolidated macroseismic database, aimed at developing the compilation and automatic processing of future macroseismic information, particularly to link complex testimony features to estimated EMS-98 macroseismic intensities. The intensities considered (EMS-98) correspond to the main observations in the database in France, i.e. from II to VI.

## AS25-1313

# Technical and scientific barriers to the practical use of physics-based PSHA

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In recent years, advances in computational resources have significantly improved the feasibility of numerical modelling of earthquake ground motions, enabling full 3D seismic wave propagation simulations from source to site. As a result, such methods are expected to become the leading tool for generating realistic ground motion scenarios for future earthquakes and for probabilistic seismic hazard assessment.

In this presentation, we examine the technical and scientific barriers that still hinder the widespread adoption of these methods in practice. We first review the performance of recent simulation databases (e.g. Cybershake) and their ability to reproduce the characteristics of seismic motions in terms of the expected ground motion and its different components of variability. We present the key elements that limit the practical use of these methods: evaluation of epistemic uncertainties (see also the abstract Liou et al.), practical difficulties in merging simulations with observations, and the challenge of simulating high-frequency ground motions in a PSHA context (computational requirements, need for high-resolution subsurface velocity structure models, and high site-to-site variability of attenuation).

Finally, recognizing the significant value of numerical simulations in seismic hazard studies, we outline a clear path forward and identify the necessary steps to enable their practical implementation in probabilistic seismic hazard applications.

## AS25-1329

# ShakeMap-EU: from real-time instrumental seismicity to historical atlases and beyond

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ShakeMap-EU is a collaborative initiative and service of the Euro-Mediterranean seismological Community that provides an integrated archive of ShakeMaps at the European level built on EPOS Seismology (ORFEUS, https://www.orfeus-eu.org/; EMSC, https://www.emsc-csem.org/; EFEHR, http://www.efehr.org/start/) services, data products and modern community software. It offers a back-up to authoritative ShakeMap (https://usgs.github.io/shakemap) implementations and delivers ShakeMaps for Euro-Mediterranean countries where local capability is not yet available while promoting ShakeMap capacity enhancement or building and collaborative research.

Following substantial efforts undertaken in the last years to strengthen the ShakeMap-EU technical framework and Community of contributors, the system is now ready to enhance its portfolio of services and outreach, in coordination with the USGS ShakeMap scientific and technical managers. Among the new services being developed are:

(a) rapid finite-fault information - project DT-GEO;
(b) information concerning earthquake-induced phenomena (landslides, liquefaction), inspired by the global USGS approach (https://earthquake.usgs.gov/data/ground-failure/background.php) - project Geo-INQUIRE and EPOS ON;
(c) an atlas of historical pre-instrumental M5.5+ earthquakes, compiled based on the earthquake source parameters from EPICA (https://www.emidius.eu/epica/), and macroseismic data available in AHEAD (https://www.emidius.eu/AHEAD/) and/or authoritative national databanks; the dataset includes about 600 historical earthquakes, providing a valuable open-access resource for the scientific community.

This initiative strengthens seismic hazard assessment and risk mitigation strategies as it bridges real-time instrumental seismology with historical earthquake studies.

## AS25-1358

# Aleatory variability and epistemic uncertainty components of the Broadband Platform simulations as part of PSHA

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Modern seismic hazard studies require quantifying aleatory variability and epistemic uncertainty of ground-motion estimates. For numerical simulations of ground motions, the six-component framework of Liou and Abrahamson (2024) is used to identify all parts of the aleatory variability and epistemic uncertainty. The six components are grouped into the method category and the parametric category. The method category refers to the algorithm and basic formulation of the simulations, and the parametric component refers to the inputs to the simulation. Each category has three parts: aleatory variability, epistemic uncertainty in the median, and epistemic uncertainty in the aleatory variability. All six components are needed for probabilistic seismic hazard analysis (PSHA) applications. We use existing simulations datasets from the Broadband Platform simulations to attempt to quantify all six components. A key missing portion is the parametric epistemic uncertainty of the median due to the uncertainty in the 3-D velocity models. Ideally, multiple 3-D velocity models would be used; however, this involves a significant effort. As an alternative, the standard deviation of the misfit between observations and predictions for past earthquakes can be partitioned into the method aleatory variability due to limitations and simplifications in the simulation method and parametric epistemic uncertainty due to the errors in the 3-D velocity model. Though the partitioning for a specific simulation set is unknown, generic percentages can be used to split the standard deviation from the validation into the method aleatory and parametric epistemic components.

## AS25-1437

# Calculation method for MM seismic intensity scale based on actual building damage data (draft)

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We proposed a method to calculate the MM seismic intensity scale based on building damage data. First, we formulated it based on the seismic intensity in Japan. Next, we obtained the MM seismic intensity scale from the relationship between the seismic intensity in Japan and the MM seismic intensity scale. By changing the period band of the response spectrum on which the calculation is based from 0.1–1 second for low-intensity seismic intensity, which corresponds to the measured seismic intensity in Japan, to 1–1.5 seconds for high-intensity seismic intensity, which corresponds to major damage to buildings, it is possible to reproduce major damage to buildings at high seismic intensity. The idea that a 1–1.5 second response corresponds to major damage to buildings is based on the authors' damage surveys around strong motion observation points and analysis of strong motion records conducted over more than 20 years. In addition, there is a physical background to this period band in which the period extends by about five times when a building suffers major damage, and it has been confirmed that this band can also be applied to earthquakes overseas, such as the 1994 Northridge earthquake, the 1999 Chi-Chi earthquake in Taiwan, and the 2011 Christchurch earthquake in New Zealand.

## S13 Recent Devastating Earthquakes and rapid response after devastating events

### AS25-0009

# Numerical Modelling of Tsunami Multi-Hazard for Eastern Indian Ocean Basin

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To safeguard vulnerable coastal populations, the development of tsunami hazard maps and early warning systems is essential. The investigation on Sumatra Subduction Zone (SSZ) represents a significant tsunami hazard for the eastern coast of India, Sri Lanka, and the Andaman-Nicobar Islands (Indo-Lankan-Andaman Arc, ILA). This study employs advanced numerical modelling to assess the potential impacts of worst-case tsunamigenic earthquakes (Mw 8.8–9.3) originating from the SSZ. Using the Method of Splitting Tsunami (MOST), the research simulates ocean floor deformation, tsunami wave propagation, and coastal inundation. Tsunami multi-hazard (TMH) parameters—wave height, velocity, arrival time, and inundation—are analysed across 75 locations in the ILA. A Multi-Criteria Decision-Making Analysis (MCDMA) framework, incorporating the Analytical Hierarchy Process (AHP), ranks the regions' TMHs as low, medium, or high. Results reveal that areas in Sri Lanka (Trincomalee, Puttalam, and Panama) and the Andaman-Nicobar Islands (North, Little, and Great Andaman; Nicobar; and Port Blair) are highly vulnerable, with expected wave heights of 8–15 m, velocities of 32–130 km/h, and inundation areas ranging from 60–80 km². These regions could experience tsunami waves within 2.5 hours of an event. Moderate TMHs are observed in other parts of the Andaman and Nicobar Islands, Sri Lanka, and Tamil Nadu, while most locations in Andhra Pradesh, Odisha, and West Bengal fall into the low-hazard category, with some exceptions due to specific coastal geomorphology. The findings may contribute to enhanced disaster preparedness, improved coastal strategies, and resilience measures, serving as valuable input for early warning systems.

## AS25-0012

# Exploring Seismic Complexity: The Hindukush and Burmese Arc in the Context of Indian Plate Dynamics

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Both the Hindukush zone (northwestern flank) and Burmese arc (northeastern flank) lie along the northern boundary of the Indian Plate. The seismic and tectonic behaviours of these regions share similarities but cannot be fully attributed to the collision of the Indian and Eurasian plates. Seismic data (1974–1988) shows Hindukush epicentres form an arc-shaped zone with two segments (E-W and NE-SW). These segments do not align with classical subduction zone patterns due to irregular depth and frequency distributions. High seismic activity in the Hindukush zone compared to its surroundings, with peak activity at approximately 36.5° N, 70.5° E and activity diminishes westward and north-eastward. Focal Mechanism Solutions of earthquakes both normal and thrust type occur. Results highlight tectonic complexity. Thrust faulting and normal faulting extend to depths of 221 km, suggests shallow dipping and tensile stresses. Proposed Model of V-shaped subduction of oceanic lithosphere is, influenced by tensile stresses (due to sinking mantle). The Compressive stresses (from mantle flow under the Indian Plate and Tibetan Plateau). Mantle sinking in the Hindukush creates vertical stretching, driving earthquake frequency and depth patterns. Comparison to Burmese Arc, similar arc morphology, but mechanisms and seismic patterns differ slightly. Both arcs exhibit complex seismicity beyond the Indian-Eurasian plate collision explanation. This detailed seismic model underscores the significance of mantle dynamics and stresses in shaping the unique tectonic features of the Hindukush region.

## AS25-0116

# Deep seismogenic processes of the 2021 M7.4 Maduo earthquake: evidence from high resolution Vp, Vs, and Vp/Vs structures

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The M7.4 Maduo earthquake on May 22, 2021, occurred within the Bayan Har block in Qinghai, China, generating a surface rupture zone approximately 170 km long. The seismogenic fault, an immature and poorly studied secondary fault, exhibited weak seismic activity prior to the event. Post-earthquake analyses of surface ruptures and aftershock locations revealed significant segmentation, yet the seismogenic environment remains unclear. Three-dimensional P-wave and S-wave velocity structures are essential for deciphering deep seismogenic environments, with Vp/Vs ratio serving as a critical parameter for characterizing material properties. However, due to sparse seismic station coverage, existing velocity models primarily depict large-scale deep crustal structures, lacking sufficient resolution for the upper crust in this region. To investigate the deep seismogenic environment and dynamic processes of the M7.4 Maduo earthquake, we employed a mount of P-wave and S-wave travel time data from a short-period dense array and applied adjoint-state tomography to obtain high-resolution Vp, Vs, and Vp/Vs structures around the source region (Jiangcuo Fault). Our results reveal a heterogeneous velocity structure, with low-velocity anomalies and high Vp/Vs ratios along the shallow rupture zone, indicative of fractured sedimentary layers and large-scale liquefaction. A high S-wave velocity and low Vp/Vs structure at depths of 6~10 km may represent a structural asperity controlling earthquake nucleation. Additionally, the S-wave velocity structure at 10~12 km depths reflects left-lateral shear deformation, consistent with long-term stress loading within the block. The observed velocity heterogeneity likely contributes to the segmentation of the Jiangcuo Fault.

## AS25-0237

# Precise aftershock activity by seafloor seismic observation in the eastern source region of the 2024 Noto-Hanto earthquake

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The 2024 Noto-Hanto earthquake with a magnitude of 7.6 occurred on January 1st, 2024. Within the Noto peninsula, an earthquake swarm has been observed since December 2020. In contrast to the swarm activity, a source region of the mainshock extends to the marine area. Therefore, we decided to conduct an urgent seismic observation using ocean bottom seismometers (OBSs) to obtain precise aftershock activity.

We deployed OBSs with an interval of 10 km using the R/V Hakuho-maru in the end of January. The R/V Hakuho-maru recovered Short-Period OBSs in the end of February. We picked up P- and S-wave arrivals manually from records by the SPOBSs and land seismic stations based on an event list by the JMA. Polarities of the first arrivals were also read to determine focal solutions. A velocity model for the location was constructed from the results of previous marine seismic surveys in the area. First, aftershocks were located using the location program with absolute travel times with station corrections. Next, we relocated the hypocenter using the double-difference (DD) method.

Depths of the aftershocks ranged from 0.2 to 17 km and become shallow compared to those in the JMA catalog. The aftershock activity seems to be limited in the upper crust and was consistent with the source fault models which were constructed before the mainshock. Most of aftershocks related to the NW–SE compressional stress. Although there are many focal mechanisms of reverse fault, some aftershocks had a strike–slip fault type focal mechanism.

## AS25-0454

# Estimation of Vs profiles of deep sedimentary layers by seismic interferometry using continuous strong-motion observation data in Antakya, southeastern Turkey

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On February 6, 2023, a Mw 7.8 earthquake occurred on the East Anatolian Fault Zone, followed by a Mw 7.5 earthquake. Severe damage was widespread across ten provinces in Southeastern Turkey. We applied the autocorrelation function (ACF) analysis to strong-motion records from AFAD and temporary strong-motion observations, in Antakya city, to estimate the depth of seismic basement. To achieve the same objective, we also applied the cross-correlation function (CCF) analysis to continuous records from the temporary observations. Recently, seismic interferometry has been utilized to investigate the depth of the seismic basement. Antakya, located in the southeastern Turkey, suffered the most severe damage. It is essential to accurately estimate the S-wave velocity structures of sedimentary layers to evaluate the long-period effects of large earthquakes and understand significant site amplification.

In this study, the ACFs from strong-motion records were used for estimating the S-wave velocity structures of the sedimentary layers using an inversion technique. The CCFs from continuous data were calculated to reconstruct the Green's functions between the stations. The group velocity obtained from the CCFs was inverted to estimate the S-wave velocity profiles using a genetic algorithm. The results showed that the depth to the seismic bedrock in the Antakya Plain is shallow.

## AS25-0567

# Fast line-source model of large global earthquakes

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Knowledge of the rupture geometry of large (M>7) global earthquakes is essential for reliable impact assessment. However, while some regions of the world have dense real-time accelerometer networks where data analysis with systems such as FinDer (Finite-Fault Rupture Detector) can constrain this geometry, in most cases it remains unknown or poorly constrained during the first few hours, a critical period for organising effective search and rescue operations. In this paper, we propose two complementary approaches that make it possible to generate a line-source model in the first hours after large global earthquakes, if the available data allow it.

One of the approaches is to replace the accelerometer data analysed by FinDer, a template matching method, with the felt reports collected by the EMSC. The other is based on the collapsing method applied to early aftershocks. This identifies seismological structures by reducing the scatter due to location uncertainties of a set hypocentres, whereby each location is collapsed towards the centroid of the locations contained in its uncertainty ellipse.

Each of these methods has demonstrated its potential in specific cases. For example, the line source model determined by FinDer when applied only to felt reports collected within 10 minutes of the M7.8 2023 Turkish earthquake, dramatically improved the early fatality estimates. The objective is to use these individual results to define the conditions for setting up an operational service and to evaluate its performance via a retrospective study.

## AS25-0582

# Frequency-dependent seismic radiation process of the 2024 Noto Peninsula earthquake from teleseismic P-wave back-projection

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A Mw 7.5 earthquake struck the Noto Peninsula, Japan, on January 1, 2024. Several studies have estimated its rupture process using seismic waveform inversion and geodetic data (e.g., Okuwaki et al., 2024; Liu et al., 2024). We performed the P-wave back-projection analysis at multiple frequencies (0.03–0.3 Hz; 0.05–0.5 Hz; 0.1–1.0 Hz; 0.3–2.0 Hz) to investigate the frequency-dependent seismic radiation of this devastating earthquake.

Our results reveal a bilateral radiation process divided into four episodes, including the clear frequency dependence: [E1] initial weak radiation near the hypocenter (0–18 s), [E2] intense high-frequency radiation between E1 and the subsequent main radiation phases (18–28 s), [E3] intense radiation in the inland region of the Noto Peninsula (25–44 s), and [E4] significant radiation in the eastern offshore region (25–44 s). During E3 and E4 encompassing the main rupture process, the inland rupture exhibits dominant low-frequency radiation (0.03–0.3 Hz), while the seismic energy emission from the northeastern offshore rupture indicates a gradual frequency transition from the lower (0.05–0.5 Hz) to higher-frequency (0.1–1.0 Hz) and the abrupt termination associated with the high-frequency stopping phase (0.3–2.0 Hz).

The presence of crustal fluids near the hypocenter, which have preceded the long-term seismic swarms since 2020, likely influences the rupture dynamics, facilitating the transition from slow to rapid rupture propagation. Complex fault geometry beneath the northeastern offshore also contributed to the observed frequency-dependent P-wave radiation. The frequency-dependent features can be a key to resolving the mechanisms of the Mw 7.5 Noto Peninsula earthquake.

## AS25-0610

# Coulomb stress transfer and fault interactions in the southern Tibetan Plateau: insights from the 7 January 2025 Mw 7.1 earthquake

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On 7 January 2025 at 01:05:16 UTC, a devastating $M_w$ 7.1 earthquake struck Tingri County, in the Tibet Autonomous Region (southwest China), killing and injuring hundreds. The ongoing continental collision between the Indian and Eurasian plates that characterises the Tibetan Plateau (TB) makes it one of the most seismically active and tectonically complex regions on Earth. This is demonstrated by the intense seismic activity in this area, where ten seismic events of magnitude M > 6 have occurred within 250 km of the Tingri earthquake in the last century. The aim of this study is to thoroughly investigate the effects of Coulomb stress transfer (CST) on the 7 January 2025 mainshock in the southern TB and the subsequent aftershock distribution. CST modelling was performed using the software Coulomb 3.4 (https://pubs.usgs.gov/of/2011/1060/). In order to determine whether the CST has played a key role in promoting or preventing fault rupture in the region, we selected both historical and instrumental seismic events of significant magnitude occurred in the last century. In addition to the individual static stress transfer analysis for each of the recent instrumental earthquakes, the cumulative CST was also analysed to obtain a comprehensive overview of the current stress scenario. Understanding the mechanisms of CST is pivotal for deciphering fault interactions and their influence on the generation of earthquakes and provides important insights into future seismic activity. This is crucial for improving seismic hazard assessment and developing effective risk mitigation strategies that ultimately contribute to build more resilient local communities.

## AS25-0643

# Integrated InSAR-Based Seismogenic Analysis and Ground Motion Simulation of the 2021 Mw 6.1 Yangbi, China Earthquake

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Rapid earthquake source characterization using geodetic observations has become critical for time-sensitive ground motion prediction and seismic hazard assessment. We present a multidisciplinary investigation of the 21 May 2021 Yangbi, China earthquake (Mw 6.1) in Yunnan Province through Sentinel-1 interferometric synthetic aperture radar (InSAR) analysis, kinematic source inversion, and physics-based ground motion modeling. Multi-track SAR data processing revealed coseismic deformation fields with maximum line-of-sight displacements of 12 cm from ascending/descending orbits. A two-stage inversion strategy employing Green's functions for a uniform elastic half-space constrained the fault geometry and slip distribution, identifying a previously unmapped blind strike-slip fault with peak slip of 0.92 m and geodetic moment of $1.4\times10^{18}$ N·m (Mw 6.06). Coulomb stress transfer modeling indicates >0.3 MPa loading on adjacent segments of the Red River Fault system, while ground motion simulations reproduce observed PGA distributions consistent with Chinese seismic intensity scale VIII in near-field areas. This study demonstrates the capability of near-real-time InSAR should be increased to resolve rapid response for earthquake disaster mitigation. Our findings highlight persistent seismic risks in the Dian-Xibei Basin's pull-apart system, advocating for stress transfer models to inform regional hazard mitigation.

## AS25-0755

# Complex Rupture Characteristics of the 2025-01-07 Mw7.1 Dingri, Xizang, China Earthquake Constrained by Seismograms and Interferometric Synthetic Aperture Radar Observations

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The complex rupture history of the 2025 Mw7.1 Dingri mainshock was analyzed through source inversion techniques and multi-source data integration, including near-field strong-motion recordings, regional broadband waveforms, teleseismic body and surface waves, and Interferometric Synthetic Aperture Radar (InSAR) observations. The three-segment fault model revealed a dominant northward-propagating rupture with three asperities peaking at approximately 4 m. The 24-second-long rupture primarily involved Faults 1 and 2, with a strike variation. Normal faulting dominated at depths above 10 km, generating discontinuous surface fractures with vertical offsets exceeding 2 m. This mainshock likely results from east-west extensional stress release associated with Indo-Eurasian plate collision. A seismic gap near the epicenter of the mainshock was identified, thereby warranting enhanced monitoring for improved seismic hazard assessment.

## AS25-0839

# Temporary seismic observations in Wajima City after the 2024 Noto Peninsula earthquake in Japan and the ground motion characteristics

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During the 2024 Noto Peninsula Earthquake, Japan (Mw 7.5), which occurred on 1st January 2024, destructive earthquake ground motion with a JMA seismic intensity of 7 attacked Wajima City in the small-scale basin (Area of 3 km square). Seismic damage was distributed in the all the area of Wajima City. Therefore, to understand ground motion characteristics in Wajima City, we installed temporary seismic stations with an accelerometer and 24-bit A-D converter at 19 sites in the western part of Wajima City from the 26th of July to the 20th of December 2025. We evaluated the site effects using seismic data in the sedimentary basin, referred to seismic data in the mountain. As a result, we found that the amplification factor is significantly higher than 10 in the frequency of around 1 Hz near the central part of Wajima City and nearly 1 in the northwestern part where the seismic damage had occurred even during the mainshock. We will also report the ground motion characteristics through the semblance analysis in this symposium to investigate the azimuthal similarity and difference of earthquake ground motion observed in Wajima City. In the future, we will compare site effects from earthquake ground motion to those from the S-wave velocity structure evaluated by the array microtremor survey to investigate whether the 1-D or 3-D basin effects are affected for earthquake ground motions in Wajima City.

## AS25-0851

# Refining the 2023 Afghanistan earthquake sequence with reported and augmented International Seismological Centre (ISC) data

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The progressive unlocking of the Herāt fault resulted in a sequence of large earthquakes, including four $M_w$ 6.3 earthquakes, in the Herāt region of Northern Afghanistan between the 7th and 11th of October 2023. Twelve earthquake monitoring agencies reported hypocentres and seismic phases for this sequence to the International Seismological Centre (ISC). Though these powerful earthquakes had significant human impact in the region, the sparse seismic network surrounding Afghanistan results in few local (<10°) or regional (10–28°) seismic phase observations being reported to the ISC. To mitigate for the limited local and regional observations, we augment the seismic phases reported to the ISC with targeted waveform picking. Firstly, to improve the epicentral location we pick the closest available stations where they are not reported to the ISC by other agencies. Secondly, we address the lack of depth resolution by picking depth phase arrivals at teleseismic distances (28–90°). Finally, for the larger earthquakes in the sequence ($M_w$ > 5.8) we calculate the earthquake moment tensor, depth and source time function using the ISC-PPSM (International Seismological Centre – Probabilistic Point Source Model) methodology. This method quantifies earthquake moment tensor, depth and source time function for larger earthquakes, along with their uncertainty. Crucially, the method provides depth resolution when the depth phases are masked by the source time function and cannot be easily picked. The combination of the data reported to the ISC, along with methods and specialities developed at the ISC provides improved resolution of this significant earthquake sequence.

## AS25-0915

# Receiver function analysis of aftershock strong motion records observed in Wajima city, Japan

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High amplitudes were observed in the northern part of the Noto Peninsula in Ishikawa Prefecture, Japan, causing building damage during the 2024 Noto Peninsula earthquake ($M_w$ 7.8). These areas are located on floodplains surrounded by hills and were also affected by the 2007 Noto Hanto earthquake ($M_w$ 6.7). Previous studies have highlighted the local site amplification characteristics in this region. The downtown area of Wajima City, which is also located on a small floodplain, has two permanent strong motion stations within 1 km of the area. During this event, JMA Wajima, located on a lowland, recorded larger amplitudes around 1 Hz than K-NET Wajima, which is located on a hill.

To investigate the spatially varying changes in site effects, we conducted temporary strong motion observations for 4 to 6 months, with a minimum distance of 150 m between 11 stations within a 3 km radius. We applied receiver function analysis to the obtained records and examined the changes in sedimentary depth. The receiver functions were calculated following Ammon (1991) at the temporary stations, using records of earthquakes with a magnitude of 3 or greater that occurred around the focal region. The Ps-P times varied, ranging from 0.4 to 0.7 seconds in the narrow sedimentary area, a characteristic that reflects the complex topography. Future studies will examine the shallow to deep sedimentary layers.

## AS25-0925

# Scientific Investigation of Large Earthquakes in China

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A large earthquake is a rare event and earthquake investigation always provides large volumes of first-hand observational data, which is greatly beneficial to earthquake sciences and socio-economics on earthquakes as well as earthquake countermeasures. Most co-seismic and early post-seismic phenomena, in terms of various parameters of geology, geophysics and geochemistry, among others, perish quickly after large earthquakes. Therefore, multi-disciplinary Scientific Investigation of Earthquake (SIE) is quite necessary, which plays an important role in understanding earthquake preparation, analyzing disaster-causing factors, and promoting earthquake disaster prevention.

SIE in China has been made rapid progress since 1966 in which year CEA was established and more than 200 case studies of $M \geq 5.0$ earthquakes have been investigated. Especially, the analysis and researches on the nine large earthquakes in the 1960s and 1970s have brought an excellent reputation domestically and internationally. Since 2000, CEA has organized over 20 comprehensive scientific investigations in large scale of personnel and disciplinary, including those for the Kunlun $M$8.1 and Wenchuan $M$8.0 earthquakes. SIE has been institutionalized and listed in the CEA's Earthquake Emergency Response Plan.

The results from existing SIE cases have revealed significant understandings such as giant surface fractures, high stress accumulation, earthquake genesis, causes of casualties, secondary disaster mechanisms and the identification of seismogenic faults. Additionally, these studies have continuously promoted the application of new technologies like remote sensing and distributed optic fiber sensing in earthquake monitoring and have provided crucial data and technical support for improving the earthquake resistant capacity of buildings, bridges, and roads post-earthquake.

## AS25-0941

# INGV Task forces and their rapid response after devastating seismic events

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Immediately after strong earthquakes, often followed by long seismic sequences in Italy, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) deploys four specialized task forces that are promptly activated to collect multidisciplinary scientific data and to generate high-quality, detailed datasets. The newly acquired seismological, geological, and macroseismic data are processed to support the INGV Crisis Unit and the Nation Civil Protection in studying and managing the ongoing seismic crisis, as well as for subsequent analyses. Two supplementary INGV task forces provide both technical-scientific and operational support to the affected population, local administrations, emergency responders, and INGV personnel engaged in field operations in the epicentral area.

The most recent major national emergency involving these task forces was the nearly year-long seismic sequence in Central Italy, which began on the night of August 24, 2016. The first team to intervene was the SISMIKO task force, which immediately deployed 24 temporary seismic stations in real-time, followed by the others: EMERGEO (surveying primary and secondary geological coseismic effects at the surface), EMERSITO (conducting measurements for site effect and seismic microzonation studies), and QUEST (performing macroseismic surveys). At the headquarters of the Department of Civil Protection, 55 shift workers took turns at COES, ensuring 24/7 coverage over 400 shifts. Meanwhile, IES operators met with the affected population and school teachers to address informational needs.

In recent years, these operational units have been continuously maintained and updated, both in terms of instrumentation and staff training, to ensure readiness for future major seismic crises.

## AS25-1052

# Aftershock distribution of the 2024 Mw7.5 Noto Peninsula earthquake in Japan: Effects of velocity structure on inland stations

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On January 1, 2024, the Noto Peninsula, Japan, was struck by a devastating earthquake with a magnitude (Mw) of 7.5. The Mw7.5 earthquake triggered a series of extensive aftershocks spanning approximately 150 km from the southwest coast to the northeast offshore region of the peninsula. While the aftershock distributions likely reflect spatial characteristics of the fault system underlying the Mw7.5 earthquake, the locations of offshore aftershocks remain poorly constrained due to the use of a simplified, land-optimized velocity model. Consequently, the detailed fault system underlying the Mw7.5 earthquake is still unraveled. To address this, we determined the aftershock hypocenters using a well-constructed three-dimensional velocity model for the Noto Peninsula. In our analysis, we employed a method based on the Markov chain Monte Carlo technique to quantify location uncertainties of earthquake hypocenters within the three-dimensional velocity model. The obtained results demonstrated that the aftershocks were determined at depths of 15 km or shallower, indicating that the Mw7.5 earthquake ruptured shallow parts of submarine faults and its rupture contributed to tsunami generation.

## AS25-1405

# Coseismic Blind Faults in the Atlas Mountains of Northern Africa: Moderate but damaging earthquakes

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The Mw 6.8 Adassil (Morocco) earthquake of 8th September 2023 occurred in the High Atlas Mountains of North Africa was damaging although relatively moderate. The Atlas Mountain range consists of a broad zone of active deformation with E-W to NE-SW trending thrust-related folding extending over 2000 km from the Atlantic Ocean to the eastern Tunisian margin. This tectonic regime also generates damaging earthquakes, the largest recorded being the Mw 7.1 El Asnam (Algeria) earthquake of 10th October 1980. The mountain ranges are limited from the Sahara (Nubia) platform by the South Atlas fault and suture zone. The fold-and-thrust tectonic domains undergo ~6 mm/yr. convergence rate between the Africa (Nubia) and Eurasia plates. Our study provides an analysis of the seismogenic potential of thrust-related folds in the Atlas Mountains based on instrumental or historical seismic events that have occurred in the region (Morocco, Algeria and Tunisia). Apart from the occurrence of the 1960 Agadir earthquake (Mw 5.9), the seismic potential along the High Atlas and its eastern continuation in the Sahara Atlas of Algeria and Tunisia was underestimated with the assumption that all major earthquake occurred to the North in the Rif and Tell Atlas. The description of fault-rupture geometry, tectonic geomorphology and paleoseismology of coseismic blind faults, along with their kinematics and elastic modeling provides the basis for a realistic seismic hazard assessment.

## AS25-1463

# Unravelling Myanmar's Seismic Puzzle: Lessons from the 2025 Sagaing Fault Earthquake

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On March 28, 2025, a magnitude 7.7 earthquake struck central Myanmar (22.013° N, 95.922° E) near Mandalay, exhibiting strike-slip motion along the north-south trending Sagaing Fault. To understand this event author analysed a time and magnitude dependent seismicity model alongside current geodynamic processes and stress patterns incorporating 94 focal mechanism solutions from the north-eastern Himalayas and vicinity. Due to region's complex tectonics, it was divided into five active zones based on seismic distribution and faulting trends, with the Indo-Burma Region (IBR) selected for detailed analysis. Seismicity data from 1963 to 2008 reveal that the IBR is highly active, having generated ten large earthquakes (M 7.0–7.8) at intermediate and shallow depths. The Kabaw and Sagaing faults dominate this zone, with the Sagaing Fault extending nearly 1200 km and capable of producing major earthquakes. The seismicity model had forecasted such an event in 2010, identifying Source 16 with an expected magnitude of 7.1 and probabilities of occurrence: 81% in next 10 years, 91% in 20, and 96% in 30. In the Arakan Yoma region, five east-west trending segments with alternating compressional and extensional stresses were identified. P- and T-axis analyses reveal that seismic activity results from both compressional (N–NE) and extensional (NW–SE to E–W) stress regimes at different depth. A high fractal dimension (Dc = 1.80 ± 0.01) suggests near-planar, heterogeneous seismogenic structures with low clustering, indicating high stress concentration due to Indian-Burmese plate interactions. However, b-value (1.00 ± 0.03) reflects typical regional stress and seismic activity.

## AS25-1464

# Testing the M8 earthquake prediction algorithm: The 2025, M7.7 Myanmar earthquake

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The M7.7 earthquake in Mandalay (Myanmar) occurred on 2025-03-28 12:50:54 local time, with epicenter coordinates 22.013° N 95.922° E at 10 km depth. More than 7.5 million people were exposed to extreme, violent, and severe ground shaking. As of April 07, according to Democratic Voice of Burma the number of confirmed victims in Myanmar has raised to 4,335 fatalities, 6,588 injured, 210 missing, and 653 rescued. This tragedy joins the list of Deadliest earthquakes since 2000 and proves again that, same as GSHAP, the Global GEM Seismic Hazard Map's "inconsistency is inadmissible for any type of responsible evaluation of seismic risk and making decisions concerning earthquake disaster prevention". Moreover, compared to GSHAP Final Map GEM has reduced by 20% the expected PGA at the site of the deadly earthquake.

According to the Global Test of predictions by the M8 and M8-MSc algorithms, conducted in real time since 1992, the epicenter of the earthquake is in the area where an earthquake in magnitude range M7.5+ was expected from January 2021. During the next semiannual updates the alert was confirmed, last time in January 2025, tentatively until mid-2027. The refinement of the alerted area by the MSc algorithm, which outlined the 390-km long area of Myamar Central Basin, misses the epicenter of the M7.7 main shock by about 70 km. The earthquake parameters may be refined in the future; however, it is evident that the event adds "success" of M8 and "failure" of M8-MSc to statistics of reliable intermediate-term forecasts of these algorithms.

## AS25-1465

# U. S. Geological Survey's Response to the March 28, 2025, Mw 7.7 Myanmar earthquake

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We review the evolution of the U.S. Geological Survey's (USGS) rapid, post-event products following the destructive 2025 Mw 7.7 Myanmar earthquake. The initial magnitude and location were spot on, followed by ShakeMap, which initially employed a point-source to finite-fault approximation, yielding initial PAGER loss estimates—generated after 27 minutes—warranting a red alert for fatalities and economic losses. We updated ShakeMap after 17 hours with a 470-km fault length estimate, informed by a combination of the proximal mapped Sagaing fault, the focal mechanism, scaling relations, finite-fault modeling, reported intensities, initial aftershocks, and array back-projection modeling provided by Wang (written communication). Though initially surprised by the enormous apparent length of the rupture, subsequent availability of initial optical and radar satellite observations confirmed the length but slightly shifted the rupture southward. We estimated the spatial and temporal rupture using a finite-fault modeling approach that indicates super-shear rupture, with slip up to 6.85 m. The ground failure product indicated significant landslide potential and more extensive liquefaction, which was later confirmed with ground-truth observations. DYFI data revealed two important aspects of the shaking. Along-fault damaging-level intensity confirmed the extent of the rupture. And, reports from Bangkok, though averaging intensity IV-V, are separable by those on ground floors who barely felt the event and those at higher floors who experienced strong, long-period motions. We deployed an aftershock forecast internationally, providing context for potential subsequent seismicity. Lastly, we show results of early site-specific building damage estimates employing building footprints, shaking estimates, and InSAR coherence changes.

## AS25-1466

# The impacts of extreme geospace weather on earthquake processes. Case study of Mw 7.7 Myanmar earthquake on March 28, 2025

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In this work, we investigate how the M7.7 earthquake in Myanmar, which occurred on March 28, 2025, responds to geomagnetic storms through a joint analysis of solar wind, geomagnetic field, and earthquake catalog. Recent research indicates that a strong earthquake may follow a magnetic storm in longitudinal regions where the high-latitude area lies beneath the polar cusp at the onset of the storm. This magnetic local time (MLT) aligns with the longitudinal extension of the polar cusp, enabling solar wind plasma to access the atmosphere directly. The expected time for an earthquake to occur can vary from several days to 1–3 months; a possible reason for this, related to upwelling mantle fluids, was discussed in Ouzounov and Khachikyan, 2024.

A powerful CME erupted from the Sun on January 1, 2025, leading to a strong geomagnetic storm (SYM/H = -112 nT), which commenced on January 4, 2025, at 02:55 UTC. During the onset of this significant magnetic storm, the Asian longitudinal region was positioned under the polar cusp. Consequently, a strong earthquake in Asian regions was anticipated between January and March 2025, which ultimately occurred. The M7.7 earthquake in Myanmar struck on March 28, 2025. At the onset of a strong magnetic storm that occurred on January 4, 2025, the magnetic local time at the future epicenter falls within the MLT interval of 08 h–16 h. Based on the magnetic storm on January 4, the expected time for the M7.7 earthquake in Myanmar is approximately 83 days later on March 28.

## AS25-1467

# Asperities on the highly segmented Sagaing fault: Implications of 2025 Mw 7.7 Mandalay, Myanmar earthquake

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An earthquake of Mw 7.7 occurred at a depth of 10 km close to the Mandalay city in central Myanmar on 28 March 2025 at 11:50 am. The epicentre is located at the intersection of the N-S Sagaing fault with E-W sharp 90o westerly turn of Irrawaddy river indicating a geometrically complex fault heterogeneity at depth. The focal mechanism shows that the earthquake occurred on a north-striking, steeply-dipping, right-lateral fault coinciding with the trend of highly segmented N-S right-lateral Sagaing fault. Modelling results based on data from broadband and strong motion stations suggest a ~460 km long rupture at supershear rupture speeds. This agrees with strong shaking and severe damage to infrastructure and residential buildings in the capital city of Naypyitaw and the surrounding areas, located more than 350 km south of the epicentre. In this paper we propose a model to show that 2025 mainshock slip nucleated in a geometrically complex asperity where transpressional features show dominance near the Irrawaddy river bend in Mandalay-Sagaing region. The rupture propagated at supershear speed following nucleation in the asperity and jumped over a fault step-over width at the restraining bend connecting two sections of the Sagaing fault and continued further through the releasing bend close to Naypyitaw in the south. The supershear earthquakes has the potential to transfer large stress and generate strong ground motion in far field distances as seen in Bangkok where skyscrapers swayed violently at 1000 km distance from the epicentre due to local site effects.

## AS25-1468

# Multi-Source Data Fusion for Rapid Damage Mapping After Earthquakes: Insights from the 2025 Myanmar Event

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The 2025 Myanmar earthquake led to significant destruction in several populated regions, many of which were difficult to access immediately after the event. This study presents an innovative approach to post-earthquake building damage evaluation by integrating satellite-based observations with supplementary geospatial datasets. The method enables rapid yet reliable assessment of structural impacts, even in data-scarce and logistically restricted areas. By combining remotely sensed information with pre-event building data and contextual spatial layers, the analysis produced detailed damage insights at the building scale. Special emphasis was placed on ensuring high accuracy in identifying severely affected zones, addressing the challenges of traditional field-based assessments under time and access constraints. The workflow supports emergency response planning by providing critical information on damage intensity and distribution shortly after the event. It also contributes to long-term recovery strategies through the identification of exposure patterns and vulnerability hotspots. The Myanmar case highlights the effectiveness of fusing diverse geospatial sources to extract meaningful damage intelligence in near-real time. This approach is transferable to other seismic contexts and supports improved situational awareness where ground truth data is limited or delayed. The results underscore the growing potential of innovative geospatial technologies in enhancing the accuracy, efficiency, and operational value of post-disaster assessments.

## AS25-1469

# The 28 March 2025 Myanmar Mw 7.8 Earthquake: Preliminary Analysis of an ~500-km Long Supershear Rupture

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On 28 March 2025, an Mw 7.8 shallow strike-slip earthquake ruptured ~500 km of the 1200-km-long Sagaing fault extending north-south across central Myanmar. This active transform fault hosted six significant earthquakes in the twentieth century and is located along the two largest cities of Myanmar, constituting a major seismic hazard. The rupture, constrained by finite-fault inversion of teleseismic body waves, back-projections of short-period P waves, and informed by initial InSAR imagery of surface deformation, has a large slip of up to 5 m extending about 100 km north of the epicenter, near Mandalay, with a patchy slip of 1–3 m distributed along 400 km to the south, with about 2 m near the capital of Nay Pyi Taw. Rupture expanded at supershear velocity of 5–7 km/s southward during the 78 s rupture duration. Long-period point-source moment tensors indicate an eastward dip of 48.5° to 60°, and such a dip is required to match the teleseismic P wave first-motions for the early large slip in the northern part of the fault. The dip may vary along the strike to the south, but resolving that will require a detailed analysis of geodetic deformation. Southward directivity associated with the finiteness and supershear rupture velocity contributed to remote shaking damage in Thailand.

## AS25-1470

# An enhanced application of the RTL Algorithm to the 2025 Myanmar earthquake

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On March 28, 2025, northern Myanmar was shaken by a devastating Mw 7.7 earthquake that caused widespread destruction and loss of life. In this study, I applied the Region-Time-Length (RTL) method retrospectively to investigate the seismicity patterns that preceded the mainshock. The RTL algorithm, which combines the spatial, temporal and magnitude distribution of earthquakes, is particularly sensitive to periods of seismic quiescence and increased activity that can precede large events.

I analyzed seismic data from the USGS catalog, focusing on the years prior to the 2025 earthquake. My results show a clear RTL anomaly marked by negative values starting about 1–2 years before the mainshock. The version of the algorithm used in this study allows the detection of quiescence not only near the epicentral area, but also throughout the region, which enables the creation of comprehensive RTL anomaly maps.

The choice of RTL parameters significantly influences the shape of the resulting signal and the spatial distribution of the anomalies, as different time and spatial windows can alter the detected patterns. To address this sensitivity, I applied two improved variants of the RTL method that were previously validated in case studies of the Central Italy Mw 6.2 earthquake (August 24, 2016) and the Sarpol-e Zahab, Iran (November 12, 2017). These improved approaches emphasize only those quiescences that persist across different parameter choices, providing greater stability for seismic monitoring and potential forecasting

## AS25-1471

# Capacity Building Enables Unique Near-Fault Observations of the 2025 Myanmar Earthquake with station NPW

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We present an overview of station NPW, installed in Naypyitaw, Myanmar, as part of the GEOFON (GE) network. The station is equipped with both strong-motion and broadband sensors and is situated 2.6 km from the Sagaing Fault, providing an exceptional near-fault recording of the Mw 7.7 earthquake on March 28, 2025. The installation and ongoing maintenance of NPW are the result of a collaborative effort between the Department of Meteorology and Hydrology in Naypyitaw and the Helmholtz Center for Geosciences (GFZ) prompted by the GFZ International Training Course on seismology and seismic hazard assessment in 2016. In this study, we provide background information about the collaborative effort that led to the installation of the only local station that provides on-scale measurements of the 2025 Myanmar earthquake. Given the widespread interest for data recorded by station, we describe the instrumental settings and data access for NPW. Given the relevance of the near-fault recordings for engineering seismology applications, we analyze key features of the mainshock,including an examination of ground motion amplitudes, frequency content, and response spectra, and near-fault effects such as fling effect and pulse-like motion. Furthermore, we review recordings of aftershocks and background seismicity at the station, and what we can learn from them.

Further contributors to this work are: DMH: Zaw Min, Tun Minn Oo, Tin Yi, Htay Htay Than, Ming-Hsuan Yen; GFZ: Fabrice Cotton, Peter Evans, Riccardo Zaccarelli.

## AS25-1472

# Supershear rupture along the Sagaing fault in the 2025 Myanmar earthquake: rupture process and relation to structure and aftershocks

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On March 28, 2025, an Mw7.7 earthquake struck central Myanmar, exposing the second and third largest cities of Myanmar, Mandalay and Naypyitaw, to intensity IX shaking, causing extensive damage and more than 3000 fatalities, but also locally strong low frequency ground motion in Bangkok more than 1000 km from the epicentre. Here, we analyse the rupture process combining strong motion and teleseismic recordings with remote sensing constraints on ground deformation. From teleseismic backprojection using multiple arrays it was possible to early on pinpoint the unusual length of the rupture of nearly 500 km. Following an initial bilateral rupture at subshear speeds, the rupture southward limb accelerated to a supershear propagation velocity of at least 5 km/s. The most energetic high frequency emission occurs near Naypyitaw ~250 km south of the epicentre, while radiated seismic energy was much smaller along the southernmost ~100 km of the rupture. We compare these observations with those from boundary-element-based, pseudo-dynamic seismo-geodetic finite slip models to provide a full description of the rupture. We further describe the aftershock sequence: aftershocks concentrate in the subshear portion of the rupture plane and in the southernmost segment, with overall less aftershocks than expected for a shallow M7.7 event. The earthquake occurred in an area previously identified as a seismic gap. However, its rupture zone extended beyond the into neighbouring segments broken in M≥7 earthquakes in 1930 and 1956. Finally, we relate the earthquake rupture to new tomographic models and background seismicity information derived from several temporary deployments in central Myanmar.

## S15 Earthquakes in low strain regions: Challenges, Advances and Opportunities – From field studies to seismic hazard assessment

### AS25-0007

# Detailed interpretation of the deep seismogenic structures of the Kangding segment of the Xianshuihe Fault Zone, Eastern Tibetan Plateau

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The Xianshuihe Fault Zone (XSHF) is one of the most active strike-slip faults on the eastern Tibetan Plateau. Along the NW-striking, left-lateral XSHF, as many as 8 M >7 and 29 M >6.5 earthquakes have occurred since 1700 CE. The Kangding segment is a particular part of the Xianshuihe Fault Zone (XSHF) with four active faults. The Kangding segment is at substantial risk of a large earthquake and plays an essential role in understanding the structural deformation pattern and analyzing the seismic hazards in XSHF. However, little is known regarding the faults deep structure in the Kangding segment. We used the deep seismic reflection data in conjunction with Magnetotelluric Sounding and earthquake depth distribution data to reveal the deep structural environment and the extension of faults to the deep part in the target area. The four branches in the Kangding segment show a flower structure and converge into one fault at a depth of approximately 15–20 km in the crust. The main fault with the steep dip is deep and cuts off the Moho. It is beneficial for the identification of seismogenic structures in the future. It is beneficial for the identification of seismogenic structures, with significant applications for medium- to long-term earthquake prediction and for mitigating seismic disaster risks in the region.

## AS25-0025

# Analysis of Strong Earthquake Risk in Maqin–Maqu Segment of the Eastern Kunlun Fault, Northeast Tibet Plateau

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The East Kunlun Fault Zone, as a highly seismically active fault, has witnessed five earthquakes with magnitudes exceeding M7.0 to the west of Animaqing Mountain since 1900. Conversely, the historical records for the Maqin–Maqu segment in the east of Animaqing Mountain show no M7.0 or above earthquakes, designating it as a distinctive seismic gap within this fault zone. We analyzed the tectonic background and structural features of the Maqin–Maqu segment within the East Kunlun Fault Zone to evaluate its potential seismic capacity. Utilizing a new established probability recurrence model, we calculated the seismic hazard for both segments over the next 100 years. The results indicate that the probability of M7.0 or above earthquake occurring in the Maqu segment in the next 100 years is 11.47%, classified as a moderate probability event. The joint probability of at least one M7.0 or above strong earthquake occurring in the entire Maqin–Maqu segment in the next 100 years is 16.14%, also classified as a moderate probability event, while the probability for the Maqin segment alone is 5.36%, classified as a low probability event. Considering the uncertainty of the probability model, a qualitative hazard classification for each segment was further conducted. The comprehensive evaluation suggests a low risk of a major earthquake occurring in the Maqin segment in the next 100 years, while the Maqu segment is assessed to have a higher risk.

## AS25-0026

# Seismic hazard assessment of the Trakošćan Castle area (NW Croatia): deterministic approach

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The assessment of the seismic hazard is carried out using a deterministic approach to determine the maximum expected earthquake ground motions in the wider vicinity of Trakošćan Castle. Trakošćan Castle, an important cultural heritage site, is located in an area characterized by moderate seismicity. Due to the repair of damage caused by recent earthquakes and the possible strengthening of the structure itself, we considered this investigation necessary. The destructive effects caused by natural seismic hazards can be minimized by reasonable mitigation measures. The analysis is performed by incorporating a seismotectonic model, data on complex morphological local soil effects, five earthquake scenarios (the Varaždin 1459, Zagreb 1880, Zagreb 1990, Zagreb 2020 and Petrinja 2020 earthquakes) important for the site under investigation, and a set of appropriate ground motion prediction equations (GMPE) to estimate the distribution of peak ground acceleration (PGA). The results for the wider area of Trakošćan Castle are presented in the form of Vs30 and a contour map of PGA for different spectral periods.

## AS25-0028

# Earthquake patterns in the low strain regime of Indian peninsular shield

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The Himalayan belt is one of the most seismically active regions of the world due to continent-continent collision between the Indian and Eurasian plates. As a result of this ongoing collision a low strain regime is developed in the Indian Peninsular shield due to the backlash of stresses that gets concentrated along weak zones in the intraplate region. Periodically, the strain energy is released in three distinct patterns. In the first type moderate earthquakes of $M \geq 5.0$ occur in the rifted margins like the west coast of India, Narmada-Son and Godavari valley. The second type exhibit scattered isolated events of lesser magnitude, and the third type are localized, shallow and short-lived earthquake swarms of very low magnitudes. We report a strong relationship of earthquake swarms with clay rich bole beds that are present as weathered zones between two consecutive lava flows in the Deccan Volcanic Province. Several of these bole beds are exposed along the road cuttings and were also encountered in core samples obtained from deep boreholes drilled to depths of ~1.5 km. The evidence of slippage along shallow faults in basalts is clearly observed as slickensides in some core samples. A mechanism is proposed that convincingly explain the shallow earthquake swarms by the combined mechanical and chemical effect of both the excess pore pressure and reduction of friction coefficient in clay rich bole beds. Absence of such a lithological control in other geological terrains of the Indian shield strengthen our hypothesis of earthquake swarms in the region.

## AS25-0031

# Seismic hazard assessment of earthquake occurrence in North East India region

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ABSTRACT

Spatial distribution of seismicity parameters like b-value, fractal dimension, energy release and recurrence period are assessed for seismic hazard evaluation in the northeast India region (88° E – 97° E and 20° N – 28° N). The present study attempts to assess the above parameters for seismic hazard evaluation. Further, the probability of occurrence of large earthquakes Mw ≥ 6.0 during a specified interval of time has been estimated on the basis of four probabilistic models namely, Exponential, Weibull, Gamma and Lognormal. Some 2702 events with threshold magnitude 3.9 from the International Seismological Centre catalogue (1964–2022) are used.

Seismicity parameter maps identified the variable stressed zones, the active fault zones and the zones of higher and lower energy release, thus indicating the areas of future probable earthquakes. The vulnerable zones identified by these maps match fairly well with the observed epicenters of the strong earthquakes (Mw>6.0) of 2016 and 2021 occurred in the region. The probabilistic models show that there is 97%-100% probability for occurrence of at least one earthquake of magnitude ≥ 6.0 in this study region in a time window of eleven to twelve years from the last earthquake of magnitude ≥ 6.0 occurred in the region in the year 2021, whereas 97%-100% probability of occurrence of at least one moderate earthquake of magnitude ≥ 5.5 in this study region in a time window of three to four years from the last earthquake of magnitude ≥ 5.5 occurred in the region in the year 2022.

## AS25-0032

# Probabilistic seismic hazard assessment for South Sichuan, China considdering small earthquake clusters

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This study conducted an analysis of seismic swarm seismicity in South Sichuan industrial area, andestablished a potential source area division model and seismic activity parameter model consideringseismic swarm activity. Analyzed the applicability of the ground motion prediction equation (GMPE)model (named as Xiao2022Chuan) established for small earthquake clusters in the southern Sichuanindustrial area, and used this attenuation relationship to conduct probabilistic seismic hazard calculationand assessment. A probability seismic hazard map of the southern Sichuan region considering earthquakeswarm seismicity was drawn, and the result was compared with the result by the GMPE used in the fifthgeneration of Chinese national seismic hazard map. This study considers the focal depth of earthquakeswarm seismicity, and assumes that all earthquakes have the same focal depth when calculating seismic-hazard. Further research is needed to determine how the difference in source depth of earthquake swarmshould be reflected in seismic hazard assessment.

## AS25-0046

# Recent strong earthquakes in eastern Himalaya region: Active transverse faults

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During last two decades, three hazardous strong earthquakes (Mw > 6.0) occurred in the eastern Himalaya region. These events are, from west to east, the 2011 Sikkim earthquake (Mw 6.9), the 2009 Bhutan earthquake (Mw 6.3) and the 2021 foredeep Assam valley earthquake (Mw 6.1); all occurred by strike-slip faulting. The aftershock investigation of the 2011 Sikkim earthquake revealed a mantle reaching near vertical fault, the Tista fault caused the main shock at 50 km depth. The 2009 Bhutan earthquake though occurred at a shallower (10 km) depth, its fault plane solution is debated to be a strike slip. The 2021 foredeep earthquake occurred by strike-slip faulting at 40 km depth in the Kopili fault (KF) zone, another mantle reaching long transverse fault. The KF caused both the 2009 Bhutan and 2021 foredeep earthquakes. The eastern Himalayan earthquakes are dominated by transverse tectonics unlike thrust tectonics on the Main Himalayan Thrust (MHT) in western Himalaya. The 1950 great earthquake (Mw 8.4) in Eastern Himalaya Syntaxis zone is also debated to have occurred at a depth 40 km by strike slip faulting. It is argued that the MHT in the eastern Himalaya may be absent, the identified active transverse faults are the potential risk zones for impending large earthquakes in the region.

## AS25-0066

# Earthquake ground motion scenarios for the cities of Varna (Bulgaria)

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A seismic hazard is a natural process or physical phenomenon, related to earthquakes and may cause loss of life, injury or property damage. Additionally, such seismic events can cause environmental damage or social and economic disruptions.

In the present study both deterministic and probabilistic earthquake scenarios for the city of Varna are generated. The city is the third-largest city in Bulgaria and the largest city and seaside resort on the Bulgarian Black Sea Coast. The city of Varna is one of the most populated (with about 350 000 inhabitants) industrial and cultural city of Bulgaria that faces considerable earthquake risk. Seismic history of Varna shows that the hazard for the city is mainly influence by the earthquakes occurred in the Kaliakra fault system.

The main objective of the study is to integrate basic geo-datasets and to assess the seismic hazard using GIS to provide a basis for disaster management of the city of Varna. The scenarios may be efficiently used for the purpose of microzonation, urban planning, retrofitting or insurance of the built environment, etc. The primary purpose of the study is to provide suitable map representations. Such maps are intended as a basic input for developing earthquake risk scenario for the city.

Hazard assessment and its associated management is a most effective approach to estimate the impact of natural hazards on the city of Varna that is situated in an area that exhibits high seismic activity.

## AS25-0097

# GIS-Based Project for SHA using the Unified Scaling Law for Earthquakes, Lake Baikal Region case study

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This study presents a GIS-based project for regional seismic hazard (SH) analysis, implemented in QGIS for the Lake Baikal region. The project consists of three components:

(i) *Identification of potential seismic sources*. SH is assessed using the Unified Scaling Law for Earthquakes (USLE), which generalises the Gutenberg–Richter law: $log_{10}N(M, L)=A+B\times(5-M)+C\times log_{10}L$, where $N(M, L)$ is the expected annual number of earthquakes of magnitude $M$ in a region of linear size $L$, and $A$, $B$, and $C$ are constants. $A$ and $B$ correspond to the a- and b-values of the Gutenberg–Richter relationship, while C reflects the local fractal dimension of earthquake epicentres. The multiscale USLE approach accounts for earthquake recurrence at different spatial scales, improving statistical estimates of rare high-magnitude events. A regional database of USLE coefficients ($A, B, C$) for grid cells ($L_0$=1/8°) is pre-installed in the project. The expected number of earthquakes of $M_j$ over $T$ years is: $N_T(M_j)=T\times N(M_j,L_0)$. The $max\{M_j\}$ satisfying $N_T(M_j)\geq p$ ($0\leq p\leq 1$) defines the Maximum Credible Earthquake (MCRE) serving as seismic intensity sources.

(ii) *Seismic Impact Modelling and Generation of seismic hazard maps (SHMs)*. A fast approximate method estimates macroseismic intensity, generating SHMs for 50 years with 10%, 5%, and 1% exceedance probabilities, considering fault strike, magnitude, and hypocentral distance.

(iii) *Verification and Comparison*. SHMs are compared with GSZ2016 and GEM2018 hazard maps and validated using 124 earthquakes (MLH≥5.5) from 3000BC to 2013AD.

The project is scalable and allowing integration of new data. It aimed to support scientific research and emergency management in earthquake-prone regions.

## AS25-0120

# A Probabilistic Seismic Hazard Assessment for Magnesia (Central Greece) by combining sensitivity analysis with complex logic tree systems

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Magnesia (Central Greece) is an all-season tourist attraction that has experienced notable seismic activity during both the historical and the instrumental era, making the assessment of its seismic hazard an important task. The Cornell–McGuire probabilistic algorithm was applied to estimate Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) for return periods of 475 and 950 years. Moreover, PGA-Hazard curves and Uniform Hazard Spectra (UHS) in terms of Spectral acceleration (Sa) were also constructed for Magnesia's key localities, i.e., Almyros, Velestino, and Volos. The first-level data used in the methodology scheme was the source area models of the European Seismic Hazard Model 2013 and 2020 (ESHM13 and ESHM20) and the earthquake catalogue of Makropoulos et al. (2012), updated until 2022. A sensitivity analysis was conducted to identify the parameters that most influenced PGA and PGV, revealing that the maximum expected magnitude ($M_u$) and Ground Motion Prediction Equations (GMPEs) were more important. Additionally, a GMPE ranking system that considers the GMPEs' standard deviation in the statistical analysis was employed. The latter aided in the management of epistemic uncertainties by creating a complex logic tree that included three possible $M_u$ values per source area and the implementation of sub-logic trees for each GMPE to account for variations in normal and non-normal focal mechanisms. The total number of branches was $3M_u \times 4GMPES^{21}$ for PGA and $3M_u \times 3GMPEs^{21}$ for PGV, with the exponential factor representing GMPE variability across the source areas of ESHM13 and ESHM20.

## AS25-0269

# Seismic hazard in the central Apennines: the PEACE project

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The PEACE (PEricolosità sismica in Apennino CEntrale – Seismic hazard in the central Apennines) project aims to improve seismic risk assessment by integrating geophysical, geodetic and geological data.

The project mainly focuses on the Central Apennines, an area extensively studied using various geological and geophysical techniques. However, these techniques have rarely been fully integrated into seismic hazard assessments due to significant epistemic uncertainties regarding the seismic cycle and fault activity. PEACE aims to address this gap by developing a more comprehensive and multidimensional hazard model, leveraging advanced data analysis and numerical modeling techniques.

A key part of the project involves constructing a 3D lithosphere model detailing the sedimentary cover structure, upper and lower crust, and mantle. This provides a more accurate understanding of the mechanical and thermal properties of the Earth's subsurface. Additionally, the project works on defining probabilistic methods to estimate seismicity rates and fault slip rates, coupling throw rates with historical earthquakes and GNSS velocities of a high-density geodetic network.

PEACE applies high-performance computing (HPC) resources to run complex simulations, integrating multiple datasets with different levels of computational complexity. This approach allows for a more detailed and realistic assessment of earthquake risks, including long-term hazard projections and scenario-based evaluations of ground shaking potential.

By integrating these diverse approaches, PEACE aims to significantly enhance the reliability of seismic hazard assessments, providing a more robust scientific foundation for earthquake risk mitigation in Central Italy. This will ultimately support better-informed decision-making for land use planning, infrastructure design, and emergency preparedness in earthquake-prone areas.

## AS25-0274

# Coulomb stress transfer modeling on tectonic faults in Northern Tien Shan

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The method of modeling transfer of Coulomb stresses on active geological faults (Stein, Nature, 1999; King et al., Bull. Seismol. Soc. Amer., 1994) has long been used in world practice, but only in last two years it begun to be applied in Kazakhstan. To date, using Coulomb 3.3 software, modeling of Coulomb stress transfer has been carried out for six active faults of Northern Tien Shan: Chilik-Kemin, Zailiysky, Almaty, Altynyemelsky, Kaskelensky and South Dzhungarsky, where several destructive earthquakes occurred. The obtained results made it possible to develop for the first time a map of seismic hazard assessment for Northern Tien Shan region based on the results of modeling the transfer of Coulomb stresses, and compare it with map of general seismic zoning in points of MSK-64 (K) macroseismic intensity scale, developed for this territory earlier. In areas of north-eastern part of Kaskelen fault, south-western part of Zailiysky fault, as well as along the South Dzhungarsky and Altynemelsky faults, the highest values of Coulomb stress (5 bar) are observed, which indicates an increased likelihood of strong seismic events occurring here in future, which is not predicted by the currently used seismic hazard assessment map in points of MSK-64 (K). Currently, these results are taken into account in expert assessments of seismic situation in the region, as well as in solving seismic forecast problems in order to avoid “missing the target” in the event of possible seismic activity maturing in these areas. Work was funded by Kazakhstan’s CSMSHE, grant IRN-AP19677977.

## AS25-0277

# Assessment of Earthquake Recurrence Parameters for the Areas of Weak Seismicity

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The presentation outlines a method for estimating earthquake recurrence parameters, specifically the b-value of the frequency-magnitude Gutenberg-Richter relationship, the mean activity rate (λ), and the area-characteristic maximum possible magnitude of an earthquake, particularly when sample data are limited. This issue is critical for seismic hazard assessments in regions with low seismicity. The method enhances the assessment of earthquake recurrence parameters by incorporating relevant information from analogous regions. Such data can be gathered from geophysics, geology, tectonics, and the seismicity of comparable areas. In cases of anthropogenic seismicity, such as mining or fracking, additional insights can be derived from observations during the exploration of nearby mines and fields. The approach employs Bayesian formalism, effectively integrating seismic data with pertinent independent information from similar regions. This proposed technique is applied to assess earthquake recurrence parameters for Poland, a region noted for its exceptionally low seismic activity.

## AS25-0309

# Aftershock analysis of the M5.5 earthquake in Archean supracratonic hard-rock formations at an unusually great depth beneath South-African-mining

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Challenges in seismic hazard assessment in low-strain regions include infrequent seismicity and sparse stations. The earthquake we report here offers us a rare opportunity to address these challenges. The Witwatersrand Supergroup is a supracratonic metasedimentary hard-rock formation. Gold mining and induced seismicity (typically normal faulting) occur in the upper Central Rand Group, while the 2014 M5.5 earthquake (with an atypical strike-slip focal mechanism) ruptured the entire depth range (3.5–7 km) of the lower West Rand Group. Mining above the hypocenter and dense in-mine monitoring enabled the ICDP DSeis project to drill into the seismogenic zone from a 2.9 km deep tunnel and retrieve core samples from the upper edge of the aftershock zone. This study cross-correlationally DD-relocated 1,500 aftershocks within a 2 $km^3$ volume for the two-week period following the mainshock, elucidating the aftershock striations aligned with intersections of the lamprophyre dike hosting the aftershocks and the sills intersected by drilling and imaged by a legacy 3D seismic reflection survey. Vp was measured at several centimeter intervals at roughly 100 locations for the 5-meter segment of drilling core. An approximately 2-meter segment of lamprophyre dike showed constant density (~3.0 $g/cm^3$), while Vp decreased from 6.0 km/s to <5.0 km/s, a reduction exceeding 1 km/s. These observations, along with the other related analyses of chemistry and petrology, imply that the intrusion of the dike and sills, followed by alteration, played a significant role in causing substantial heterogeneity in rheology and stress in the Archean supracraton hard-rock formations, ultimately controlling aftershock generation.

## AS25-0317

# Seismicity and strain rates in the Carpathian region: Integrating GPS data, focal mechanisms, and fault systems

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The Carpathian region, located at the edge of the East European Craton, presents a unique tectonic environment where subduction ceased more than 9 million years ago, yet crustal deformation and seismicity persist, challenging our understanding of intraplate earthquakes and the processes driving these phenomena in stable continental interiors. In this study, we use over two decades of GPS data from more than 100 permanent stations to estimate both horizontal and vertical crustal motions, constructing the most accurate and high-resolution model of crustal deformation and strain-rate in the region to date. Our results show a southward drift of the South Carpathians and Moesia relative to Eurasia at 1.5 mm/yr, along with complex vertical motion in the foredeep, suggesting localized uplift from slab break-off. We compare these GPS-derived strain rates, maximum shear strain, and dilatation patterns with earthquake focal mechanisms, known fault zones, and geological boundaries. Our findings reveal a strong correlation between surface deformation and seismic activity, highlighting the influence of both deep Vrancea slab dynamics and surface plate kinematics on seismicity in this low-strain rate region.

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## AS25-0322

# Challenges in characterizing faults for Probablistic Seismic Hazard Assessment in Low Strain Regions

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Over the past few decades research has recognized different styles of earthquake occurrence on faults in low strain regions (LSRs). Some LSR faults exhibit a classic plate-boundary stick-slip pattern producing repeated large magnitude earthquakes with recurrence intervals on the orders of >104–106 yrs (e.g. Meers fault). Other faults produce earthquakes with episodes of clustered activity (multiple ruptures) separated by similarly long (~104–106 yr) intervals of quiescence (e.g. Cadell Fault) and still other faults generate single, one-off events, with no evidence of a penultimate earthquake (e.g. Tennant Creek fault). These different styles of earthquake occurrence in low strain regions pose a challenge when incorporating individual faults into hazard models.

Current modelling practice often uses a fault's slip-rate and associated earthquake recurrence interval to compute hazard, which requires an understanding of the fault's earthquake occurrence behavior (i.e., quasi-periodic, clustering & quiescence, one-off). However, these phenomena are often poorly understood. To overcome the modeling uncertainty associated with earthquake occurrence on faults in LSR's, analysts can implement a logic tree approach. This approach can be used to capture the epistemic uncertainty in earthquake occurrence for LSR faults where unique branches of the logic tree capture alternative occurrence models. The challenge then becomes how to assigned defensible weights to the alternative models. Information regarding earthquake occurrence models and recurrence behavior for LSR faults is still required and therefore targeted investigations should be carried out to support seismic hazard assessments for critical facility engineering.

## AS25-0344

# Active faulting in the W-Alps as seen by GNSS: observations and modeling

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Quantifying active faulting in the slow-deforming and moderately seismic Western Alps remains a scientific challenge. However, updated GNSS solutions integrating 25 years of GNSS data allow to evaluate slip and strain rates of 0.1–1 mm/yr. In particular, we can now compare the already confirmed High Durance fault (HDF) activity in the Alps' internal zone with the Belledonne Fault (BDF) (external zone).

Strain rate estimates are larger across HDF (19 ± 3 nanostrain/yr EW extension, 7 ± 2 nanostrain/yr perpendicular compression) than BDF (5 ± 1 nanostrain/yr EW compression, 2 ± 1 nanostrain/yr extension). Fault slip rates indicate dominant dextral strike-slip motion on BDF (0.3 ± 0.2 mm/yr) with minor compression, while HDF exhibits major extensional motion (0.3 ± 0.1 mm/yr) with a minor dextral slip component. These two faults represent the broader kinematics of the W-Alps: mainly extensional deformation in the internal zone (HDF) and strike-slip motion in the external zone (BDF).

We developed a rigid 3-blocks model, encompassing HDF and BDF, to explore their relative coherency. This model explains 29% of the observed GNSS velocity field and confirms the HDF and BDF deformation styles. In particular it shows that HDF and BDF play interconnected roles in the W-Alpine deformation framework. The residual GNSS station motions could be due to internal block deformation (e.g. unaccounted secondary faults), or volume forces, which may be responsible for a noticeable part of the actual Alpine dynamics, but which are not taken into account in our block model.

## AS25-0365

# Testing the best modeling techniques for earthquake-related long-term geodetic transients

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Major earthquakes can produce evident offsets in geodetic time series up to dozens of kilometres far from their epicentres. Moreover, the viscoelastic relaxation along faults and within the adjoining crustal volumes foster slow geodetic transients called 'afterslip'. They usually last for months or even years and are usually modelled using exponentials. Recently, evidence has been collected that the seismic cycle can affect GNSS time series for decades. These observations challenge the idea that geodetic recordings can be considered stationary over human-life time intervals and only affected by periodic modulations induced by seasonal loading, tides and anthropic activities. Here, we compare three different models for dozens of long-term afterslips in suitably pre-processed GNSS daily data series: exponential, power law and stretched exponential functions. The exponential arises from a purely viscoelastic behavior of faults, a power-law attenuation can be produced by a suitable sum of exponential relaxation process or power-law fault rheology, while the stretched exponential can be derived assuming geodetic contributions from crustal volumes with heterogeneous rheology. We prove that stretched exponentials can be used for the reliable prediction of future developments of afterslip in GNSS time series being comparable or even superior to both exponentials and power laws in fitting both in the short- and long-term trends. We also provide a physical motivation to support their occurrence in terms of stress redistribution in the crustal volumes surrounding major faults.

## AS25-0405

# Seismic Potential of the Laikipia-Marmanet Segment: Insights from Monte Carlo Simulations

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The 1928 Subukia earthquake, which occurred along the Laikipia-Marmanet fault (LMF) of the Kenya Rift, remains the most significant earthquake event ever recorded in Kenya. The fault was activated repeatedly during the late Quaternary, with evidence of six ground-rupturing earthquakes, as part of the tectonically active East Africa Rift Systems. Despite the dike intrusion that are believe to limit large earthquake occurrence, the LMF and other unmapped faults remains potential of generating large earthquakes. Traditional probabilistic seismic hazard assessment (PSHA) that rely on short instrumental records may underestimate the risk posed by such faults.

This study employs Monte Carlo simulation to assess the seismic potential of LMF, integrating geological, geophysical and earthquake catalogue data to generate synthetic earthquake catalogues. Key input parameters, including fault length, slip rate, and magnitude-frequency relationship, were derived from geology and gravity, with empirical scaling laws by Well and Coppersmith (1994) guided magnitude estimation. The simulation generated synthetic earthquake catalogue that model a wide range of potential seismic scenarios, utilizing both characteristic earthquake model and Gutenberg-Richter distribution. In addition, gravity data were analyzed to refine the fault's geometry.

The findings suggest a significant probability of large-magnitude (Mw> 6.5) earthquakes along the LMF. The synthetic earthquake catalogue aligns with paleostudies evidence, revealing potential ground rupture scenarios. The study shows that the PSHA models, which depends on limited data, may significantly underestimate seismic hazard in the area. The application of Monte Carlo simulation, geological and geophysical data provided a more robust and reliable assessment of the fault's seismic potential.

## AS25-0444

# Integrated Probabilistic Seismic Hazard, Microzonation, and Structural Damage Potential Modeling for the Tectonic Province of Central India

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Central India, comprising Madhya Pradesh and Chhattisgarh, is bounded by the Son Narmada North Fault and the Central India Shear Zone, characterized by Precambrian rock formations, deep-seated fault systems, and a protracted history of reactivated tectonic activity. The prevailing hazard evidenced by the earthquake-related fatalities in the region, such as 1997 Jabalpur Earthquake ($M_W$ 5.8), serves as a reminder of the uncertainties in shield seismicity, highlighting the necessity of investigating this seismogenic environment. Probabilistic Seismic Hazard Analysis (PSHA) has been conducted using the classical Cornell-McGuire method, incorporating both polygonal and tectonic sources across two hypocentral depth ranges (0–25 km and 25–70 km), and 15 Ground Motion Prediction Equations including 6 Site-specific Next Generation Spectral Attenuation models through a logic-tree approach to produce Peak Ground Acceleration (PGA) ranging from 0.06–0.37 g for 475-years of return period at engineering bedrock. The effective shear-wave velocity ($V_S^{30}$), determined through geotechnical and geophysical investigations and supplemented by topographic-gradient in data-scarce regions, classifies the region into site classes from E/F ($V_S^{30}$≤180 m/s) to A ($V_S^{30}$>1500 m/s). Furthermore, surface-consistent PSHA considering site response analysis yields an amplification of 1.11–2.71, and a PGA of 0.08–0.76 g. A micro-level seismic hazard study of Indore, the commercial capital, integrates multiple geo- and seismic-hazard themes, categorizing the city into five zones. Additionally, a structural damage potential model using SELENA incorporates probabilistic ground motion, building typologies, vulnerability functions, inventory data, and socio-economic information to estimate damage and casualties. This model is expected to foster seismic-resilient urbanization by offering precise disaster management strategies and mitigation measures for the region.

## AS25-0528

# A new national seismic hazard assessment for continental Norway and the Svalbard archipelago

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This study aims to develop a new probabilistic seismic hazard model for Norway and the Svalbard archipelago following recent advancements in earthquake hazard estimation, driven by new methods, tools, and more complex processing routines and calculations. Norway, located on the western edge of the stable Fennoscandian shield, experiences low to moderate seismicity, with events rarely exceeding magnitude 5.5. In contrast, Svalbard has seen moderately sized events close to population centers in recent years. The study area encompasses continental Norway and the Svalbard archipelago, including a 300 km perimeter. Hazard estimates are calculated using the OpenQuake Engine, with input data sourced from the Norwegian National Seismic Network and supplemented by other national and international catalogs. The catalog constitutes a significant improvement with the addition of five years of earthquake data, a lower minimum magnitude, automated quality assurance, and data harmonization with neighboring regions. The study is supplemented by a smoothed seismicity model, in addition to traditional area zonation, and the applied ground motion models are validated against local data records. The analysis results in an up-to-date and improved open-access evaluation of seismic hazard in Norway. This new hazard model supports better preparedness and enhances understanding of the economic and societal risks posed by earthquakes. The methods and input data used for the analysis will be presented, along with results, and discussed in the context of ESHM20 and other regional hazard assessments

## AS25-0548

# Integrating GNSS for an Adapted Methodology to Connect InSAR to an Earth-Fixed Terrestrial Reference Frame in Northern Algeria

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The deformation measurements provided by InSAR are relative, creating a free network referred to an arbitrary point of reference (RP) assuming to be stable. In this study, we analyze the line-of-sight (LOS) displacements from Sentinel-1A/1B satellite images collected between 2015–2023 along the ascending and descending tracks, using the Permanent-Scatterer (PS) method to measure and quantify active surface deformation at high spatiotemporal resolution. Our focus is on the Asnam and Boukadir fault system, a **low-strain region**, in the northwestern part of Algeria. We present an adapted methodology to connect LOS velocities from InSAR to an Earth-fixed terrestrial frame (ITRF2014) using GNSS continuously operating reference stations (CORS). Our methodology consists of three steps: (i) decomposing ascending and descending LOS velocities into 3-D components (vertical, easting, and northing); (ii) establishing a uniform transformation between the InSAR reference point (RP) and velocity rates from GNSS-CORS; and (iii) applying the transformation model to all pixels of the 3-D velocities obtained in step (i). This approach enhances the reliability of interpreting observed physical motion. By providing the mean velocities components of the EECH GPS-CORS station in ITRF2014 with three reference options (fixed-EU, fixed-NU, and No Net Rotation), we generate five kinematic motion models compared to those found elsewhere in the tell Atlas and nearest region from the offshore. Our study provides new insights into the deformation processes in **low-strain regions**, contributing to improve **seismic hazard assessment** for North Algeria.

## AS25-0646

# Joint seismic hazard assessment of slow slip rate faults in Northern Greece using InSAR, GNSS and field analysis

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Greece's complex geotectonic setting, driven by the subduction of the African plate beneath Eurasia and the movement of the Anatolian microplate, results in significant seismic activity. While high-slip-rate faults have been extensively studied, slow-slip-rate faults in Northern and Central Greece remain poorly understood due to their long recurrence intervals. This study integrates advanced remote sensing techniques, InSAR time-series analysis, geodetic data and processing techniques with field-based analyses to investigate active faulting in Northern Greece, focusing on the Kavala-Xanthi-Komotini and Kozani-Grevena fault zones while aims to assess the kinematic and quantitative characteristics of these slow slip rate faults to improve seismic hazard assessment. Geological mapping, paleoseismological analysis, and morphotectonic investigations were applied to quantify fault activity and recurrence intervals. GNSS time-series analysis was applied to identify rate velocities and Sentinel-1 SAR data were processed using Differential Interferometric SAR (DInSAR) to detect ground displacement, with phase unwrapping and vertical displacement calculations performed within SNAP Desktop software. Additionally, the Environmental Seismic Intensity (ESI 2007) scale was applied to evaluate surface effects such as uplifts, subsidence, ruptures, and slope failures, which were mapped and digitized in a GIS framework. Isoseismal maps were produced using kriging interpolation, while traditional field data were used to validate remote sensing findings. Thus, understanding these faults is crucial for refining seismic regulations (e.g., Eurocode 8) and improving hazard mitigation strategies. The results will support earthquake preparedness efforts, seismic hazard assessment and contribute to the broader understanding of slow-slip-rate fault behavior in low strain regions worldwide.

## AS25-0667

# Evaluation of NGAEast GMPEs for Application in Brazil

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Despite the low intraplate seismicity in Brazil, seismic hazard is important for critical facilities such as nuclear plants and tailings dams. Following international standards, the Brazilian Mining Agency required tailings dams to be re-evaluated considering 10,000 years ground motion, which can exceed 15%g. The selection of GMPE models is a key step in PSHA studies, often relying on equations from other intraplate regions without proper validation. We compared the NGA-East models with Brazil's available "strong"-motion database, consisting of accelerations recorded by seismographic stations for 20 earthquakes (mb 3.0–5.7). Vs30 for site corrections were measured in most of the seismic stations using MASW and H/V methods. The measured accelerations were converted to a hard-rock condition (Vs30=3000 m/s) for comparison with the NGA-East models. Most seismic stations use velocity sensors with low sampling rates (50–100 sps), which underestimate PGA values compared to accelerographs. This causes PGA values to be lower than would be observed in a proper accelerograph, especially for distances less than 50 km and magnitudes lower than 4.5 mb. An attenuation factor, dependent on distance and magnitude, was devised to correct the database, reducing data scatter. A residual analysis (RMS) and log-likelihood score (LLH) comparison of corrected PGA data with NGA-East models identified USGS_04 as the best GMPE (fixed weight = 0.3). To ensure adequate CBR coverage, we also selected USGS_2, USGS_13, Graizer, and USGS_10, with weights of 0.193, 0.182, 0.175, and 0.150, respectively. These weights were computed using the inverse of LLH and RMS, normalized to sum 1.0.

## AS25-0705

# Seismic hazard map for the southern part of the Netherlands

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Natural seismicity in the southern-eastern part of the Netherlands is related to the fault system of the Ruhr Valley Graben. The largest earthquake in the instrumented era to date is the 1992 $M_L$ 5.8 ($M_w$ 5.4) earthquake in Roermond. The hazard map available so far was based on macroseismic intensity. Probabilistic Seismic Hazard Analysis was performed for Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV), and for return periods of 475 and 2475 years. Standard rock conditions ($V_{S30}$ = 800 m/s) do not apply in the Netherlands, where $V_{S30}$ ranges from ~ 80 and 400 m/s. Epistemic uncertainty was included by a logic tree approach. The logic tree was populated by two seismic zonation models and three suitable Ground Motion Prediction Equations of equal weights. Sensitivity analysis showed that GMPE results within three standard deviations need to be included to account for aleatory variability. The resulting hazard maps show maximum mean PGA values of 0.95 m/s$^2$ and 2.0 m/s$^2$ for return periods of 475 and 2475 years respectively. The corresponding maximum mean PGV values are 0.056 m/s and 0.13 m/s. The influence of the Ruhr Valley Graben is clearly delineated on the maps. PGA values for rock conditions and a return period of 475 years were compared to seismic hazard maps from neighboring countries. Our hazard map values are significantly lower than the EC8 zonation map of Belgium and the 2016 German seismic hazard map, but compare well with a recent seismic hazard map for Wallonia, Belgium.

## AS25-0762

# Fault-based Probabilistic Seismic Hazard Assessment of Tunisia

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Although Tunisia is classified as an area with moderate seismicity, the region experienced several large earthquakes in the past. The Historical catalogue reports the occurrence of destructive earthquakes such as the (Kairouan in 859 Mw=6.8...).

This work aims to build a probabilistic seismic hazard assessment based on active faulting, historical and instrumental seismicity, paleoseismology, archeoseismology, seismotectonic, geophysical and geodetic results for Tunisia. The first step is devoted to the construction of the homogeneous catalogue with conversion of different magnitudes (Ml, mb, Md, Ms) and intensity into moment magnitude (Mw) from the Kharrat et al. (2014) and ISC catalogues. The seismicity is tested for gaps of seismic records and magnitude of completeness, with the G-R distribution (b-value) and determination of Mmax. Using the database of seismicity, active tectonics and fault rupture mechanisms, the study region is subdivided into 11 source zones. The seismic strain rate is obtained from the earthquake distribution, the fault slip rate and GNSS results to characterize the seismic slip deficit for each active zone. The seismicity, active faulting and seismic strain parameters are estimated for each source zone, that include input variables for the seismic hazard estimation. We use R-CRISIS code based on the classical Cornell–McGuire method to implement the probabilistic approach of the seismic hazard assessment. Finally, it is then essential to evaluate to what extent the methods applied for the characterization of the seismic hazard, developed in regions with high seismicity are valid for areas with present-day moderate seismicity comparable to Tunisia.

## AS25-0785

# Quantification of uncertainty in the hazard estimates for the UK offshore Exclusive Economic Zone

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Mosca et al. (2024) developed a new seismic hazard model with accompanying hazard maps for the offshore region around the United Kingdom (UK), the UK Exclusive Economic Zone (EEZ), for peak ground acceleration, spectral acceleration at 0.2 s and 1.0 s for 5% damping on rock conditions using a Monte Carlo-based approach for probabilistic seismic hazard analysis (PSHA). This addresses some of the limitations of the 2020 national seismic hazard model for the UK (Mosca et al., 2022) and estimates realistic uncertainty in the input parameters and models to account for the inherent limitations of the data in low seismicity intraplate regions where the earthquake catalogue may not reflect the long-term hazard due to the low deformation rate in this region.

The biggest advance from the 2020 national hazard maps to the 2024 offshore maps is the first-time quantification of epistemic uncertainty (described by the 50$^{th}$, 16$^{th}$, and 84$^{th}$ percentile) in the hazard results for selected sites in UK waters using a Monte Carlo-based approach for PSHA. Although there have been a few attempts in the literature, to our knowledge, there is no well-established procedure to infer the fractile hazard curves using the Monte Carlo-based PSHA. The approach for the uncertainty quantification and, in general, any PSHA based on Monte Carlo simulations are computationally efficient in low seismicity regions, such as the UK, when a logic tree is complex and contains many branches.

## AS25-0836

# Systematic Estimation of Earthquake Source Parameters for Continental Australia: Consequences for Earthquake-Hazard Assessments

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For the first time, a systematic assessment of stress drop and moment magnitude has been undertaken for over 290 earthquakes occurring within Australian continental crust using a new continental-scale attenuation model. The attenuation model uses more than 6,100 individual earthquake recordings and is valid for hypocentral distances up to 2,000 km. Estimates of stress drop are spatially variable, with north-western Australia having consistently high values of stress drop, while south-western and eastern Australia—on average—have relatively low stress drop. The moment magnitudes calculated through this study are used to assess the utility of magnitude conversions applied in previous seismic-hazard studies in Australia. In particular, the relativity of moment magnitude and local magnitude is found to be strongly dependent on the stress drop of the earthquake, with high-stress-drop events having relatively higher values of local magnitude. These observations will have consequences for the selection and regionalisation of ground-motion models and magnitude conversions used in future national- and site-specific seismic hazard assessments in Australia.

## AS25-0882

# Seismic Hazard of salt-controlled normal faults. Insights from the Southwestern Valencia Trough (E Spain)

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The seismogenic potential of active faults is often estimated using empirical source-scaling relationships. These relationships correlate geometric fault features (length, area, etc.) with key seismogenic parameters, such as potential maximum magnitude (Mmax). Source-scaling relationships typically assume a homogeneous seismogenic crust. This study addresses the Southwestern Valencia Trough, where we define and characterize three active normal faults: the Cullera Fault, the Albufera Fault, and the Valencia Fault. These are salt-controlled faults, influenced by a mechanically weak layer consisting of a thick evaporitic succession. We discuss the role of this weak layer in coseismic rupture propagation and its implications for source-scaling relationships. We propose that, in regions with a heterogeneous seismogenic crust, empirical relationships could be refined by using the fault area weighted by the aspect ratio. Our approach yields a Mmax considering a heterogeneous crust that is 4–15% lower compared to estimates that assume a homogeneous crust.

## AS25-0883

# Geological evidence of Quaternary activity in the Moreras Fault (Eastern Betic Cordillera, SE Spain)

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One third of the 4–6 mm/year convergence between the Nubian and Eurasian plates is presently accommodated in the SE Iberian Peninsula. In the Eastern Betic Cordillera, most of the current deformation is concentrated within by the Eastern Betic Shear Zone (EBSZ). However, tectonic activity appears lower south of the EBSZ, in the Águilas Tectonic Arc. Historical and instrumental seismic records are scarce, and the potential markers of Quaternary activity are partially obscured due to limited sedimentation since the Pliocene and the impact of intense human activity. In this study, we characterize the western sector of Las Moreras Fault, one of the main structures within the Águilas Arc. We present a new detailed mapping of the fault trace, together with a structural characterization, and new geological evidence of potential Quaternary activity. The Moreras Fault extends at least 16 km onshore with a dominant N100E strike and a primary right-lateral slip component, along with secondary dip-slip motion. It consists of multiple strands that define two main fault zones, which bound an uplifted block between of Paleozoic-Triassic basement between them, with one fault zone to the north and the other to the south. These fault zones deform the Early Miocene to Pliocene marine deposits of the adjacent basins. However, evidence of Quaternary deformation is subtle. In some areas, Pleistocene alluvial fans exhibit deformation caused by fault strands, which may indicate Quaternary tectonic activity. These findings highlight the need for further studies to assess active deformation in this structurally complex region.

## AS25-0894

# Local, regional and teleseismic source estimates for small earthquakes in the Granada Basin (Spain)

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The Granada Basin and central Betic Cordillera (S-Spain) experienced destructive magnitude 6 earthquakes in historical times. However, large events are infrequent in this slowly deforming region and instrumentally recorded seismicity culminates in a handful of M ≳4.5 events, hindering a complete identification and characterization of seismogenetic structures. We show how three different approaches for source inversion can be combined to get a comprehensive picture of the seismotectonic situation: 1) We reanalyze instrumental seismicity since the installation of the local short-period network in the late 1980s, to detect and relocate earthquake multiplets and map the orientation of active fault segments. In combination with polarity readings, we determine constrained multiplet focal mechanisms. 2) We apply regional, intermediate-period moment tensor inversion to events with M ≳3.5 since the late 1990s, when regional broadband recordings become available. 3) We use beamforming from teleseismic arrays and waveform modelling of depth phases to estimate depths and mechanisms for events M ≳4.5 since the late 1970s. As a result, we can confirm the seismogenetic nature of several recognized normal faults in the Granada Basin, in part without prior geological or paleoseismological evidence of recent activity, and of unmapped high- and low-angle fault segments at mid-crustal depths. Mid-crustal multiplets show constant event production rate, indicating ongoing aseismic creep of the basal detachment below the basin, with ~5° dip and hanging wall motion towards SSW. Several high-angle faults seem to merge into the detachment and represent relevant faulting sources with locking depths of ~10 km.

## AS25-0899

# Reassessing earthquake magnitudes and ground motion in northwestern France: implications for seismic hazard in a stable region

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The northwestern part of mainland France is considered a tectonically stable region but experiences recurrent moderate earthquakes (Mw > 4), such as the Layon (2019, Mw ~4.2) and La Laigne (2023, Mw 5) events. Ground motion prediction models (GMMs) currently used for seismic hazard assessment have not been specifically validated for this region. Recent studies (Ramadan et al., 2024) have shown significant discrepancies between observed ground motions in this region and predictions from the Italian GMM (Lanzano et al., 2019), particularly an enhanced high-frequency content and lower amplitudes at low frequencies. However, these results are limited by large uncertainties in Mw estimates, which may be overestimated due to magnitude conversion laws (Laurendeau et al., 2019). In this study, we reassess the Mw values of earthquakes in the French Résif strong-motion database (Traversa et al., 2020) using the SourceSpec method (Satriano, 2025). Our preliminary results indicate systematically lower Mw values than those in the original flatfile, with differences of up to 1 Mw unit. Using this revised dataset, we analyze the ground motion characteristics in the region and assess the applicability of multiple GMMs. This work provides new insights on ground motion prediction in low-strain regions and contributes to improving seismic hazard assessment in northwestern France.

## AS25-0903

# Fault kinematics and slip rates in SE Spain. GNSS constrains

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The Eastern Betic Cordillera stands as one of the most seismically active regions withinSpain. This seismicityis related to the complexgeodynamic framework associated with theNubia-Eurasiaconvergence. In this study, we present the horizontal velocity fieldfrom SESpain, a result derived from newly acquired GNSS data. Eurasia fixed relative velocitiesexhibit a predominant north-northwest to north direction, with magnitudes ranging between1 to 2 mm/yin the southern sector of the study area. In the western and northeasternsectors, movements of approximately 1 mm/yhave been determined. The northern sectorof the study area is characterized by velocities that are slightly above 0 mm/y. Furthermore,the rates of shortening or extensional movement, as well as lateral displacement, havebeen calculated for three selected active faults. Regarding the Las Moreras Fault, ourcalculations produced a shortening rate orthogonal to the fault trace of0.2±0.2 mm/yanda dextral fault-parallel movement of 0.3±0.2 mm/y. In the case of the Carrascoy Fault,ashortening rate of0.0±0.2 mm/y and a lateral displacement of 0.1±0.2 mm/y are calculated. With respect to the Crevillente Fault, a shortening rate of0.3±0.3 mm/yand a sinistraldisplacement of 0.6±0.3 mm/yare estimated.

## AS25-0908

# Relocating seismicity in Portugal using a high-resolution earthquake catalog

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Mainland Portugal is located in a typical intraplate setting, where seismicity is usually classified as diffuse, characterized by low-magnitude events (<M4), and sporadic larger events, that occur within a slowly deforming lithosphere. However, seismicity may be poorly located, affecting its interpretation. Furthermore, some seismic activity does not seem to have happened near any mapped fault, which may indicate that the potentially active fault map is incomplete. An accurate depiction of active seismicity is crucial for enhancing our understanding of the tectonic processes occurring in the crust and for better evaluating Portugal's seismic hazard and, therefore, improving measures to reduce seismic risk.

Our study aims to relocate seismic events in the region leveraging the standard Portuguese earthquake catalog and a deep-learning based catalog. We use NonLinLoc to constrain better the absolute and relative locations of the combined catalog. We first test the robustness of the regional seismic velocity models IGN1D, PRISM3D, and PT3D and the NonLinLoc package for absolute locations, with and without source-specific station terms (SSST). Then we add inter-event waveform similarity information (NLL-SSST-coherence) to relocate the events. To test our methodology, we first focus on the Arroiolos seismic zone where a M4.9 occurred in 2018. Preliminary results in this area suggest improvements in the accuracy of seismic locations, allowing for better identification of seismogenic clusters and lineations. We do not find significant differences between the chosen velocity models. Finally, we discuss the relation between the results and the surrounding geological structure.

## AS25-0909

# A deep learning-based seismic catalog for Iberia: New insights into seismicity and anthropogenic activity at an intraplate region

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Understanding the seismic behavior of slowly deforming regions (≤1 mm/yr) remains challenging due to small tectonic loading rates, complex fault systems, and episodic seismic activity, which complicate subsurface imaging and hazard assessment. Combining deep-learning techniques and dense seismic recordings, we refine the earthquake catalog for Iberia, a slowly-deforming region in Southwest Europe, to better characterize its seismicity.

Between 2007 and 2014, several dense temporary seismic networks were deployed in Iberia that hold untapped data. We retrained the deep-learning earthquake detector Earthquake Transformer (Mousavi et al., 2020) using 28,622 regional waveforms and applied it to these datasets. Our new model detected 98% of the seismic phases in the standard earthquake catalog up to epicentral distances of 250 km. Applying our model to the 7 years of data, we compiled a catalog of 70,057 events. However, a closer inspection of the detected waveforms revealed possible contamination from anthropogenic sources. We applied a deep-learning earthquake-explosion discriminator and determined that only 38,901 (56%) of the detected events originated from earthquakes. The new catalog enhances previously identified lineaments and reveals new seismic clusters, such as one associated with the widely felt M4.8 February 2025 earthquake near Lisbon. Notably, areas with high concentrations of anthropogenic events also coincide with identified active faults and historical seismicity, particularly in Northern Portugal and Catalonia. Therefore, further studies are needed to understand the connection between tectonic structures, natural seismicity, and anthropogenic activity in the region.

## AS25-0923

# Unexpected seismicity in/and unknown sources at intra-plate settings: the Mw 5.1 Sparta, North Carolina, USA co-seismic surface deformation example

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In early August 2020, an Mw 5.1 earthquake ruptured along a previously unknown fault and generated a co-seismic rupture, near the village of Sparta in North Carolina. This earthquake resulted from a shallow and complex rupture along two small fault strands, one reverse fault reaching the surface and producing a co-seismic scarp, and the second a blind strike-slip fault. The earthquake occurred outside the regional seismic zones where no relevant seismicity has been recorded. The Sparta village was impacted and circa ~600 houses were affected, causing a ~$20 M economic impact.

In the following months, an holistic research combining geological field surveys, with InSAR, lidar, UAV imagery, geophysical surveys, geodesy, and seismology, allowed to corroborate the existence of a fault zone, trending anomalously to the regional tectonic fabric.

Specifically, the post-earthquake lidar data allowed us to recognize a subtle but broad co-seismic deformation zone, that impacted Sparta's infrastructures. Furthermore, paleoseismology investigations revealed that there had been a recurrence of surface ruptures during the past 100 ka, indicating this was not a "one-time" event.

This earthquake is an example of Quaternary reactivation of pre-existent structures, in a low-strain tectonic setting, raising questions regarding recognition of recency of activity in faults, especially if located outside known seismic zones. The combination of several datasets enhances the recognition of subtle but possibly impactful co-seismic deformation, suggesting that similar earthquakes may have been poorly characterized and that they may be more frequent than expected.

## AS25-0932

# Integrating Seismological and Geodetic Data for Stress and Strain Analysis in the Slow-Deforming Region of East Macedonia and Thrace, Greece

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East Macedonia and Thrace, located in northern Greece and north of the dextral shear zone of the North Aegean Trough (NAT) and the extensional tectonics of the Aegean region, is considered as a slow-deforming region, compared to the more active Mygdonia extensional basin to the west and the NAT to the south. The study area still experiences sporadic seismicity and distributed deformation dominated by normal and strike-slip faulting. Previous geodetic and seismological studies have provided insights into the regional kinematics and stress regime, but a comprehensive investigation integrating new focal mechanism solutions and strain analysis is still lacking due to the lack of strong earthquakes in the region. This study aims to compute new focal mechanisms for low and moderate-magnitude earthquakes in the region to reconstruct the regional stress regime. In addition, a strain analysis is performed using geodetic data to quantify deformation rates and investigate the deformation pattern of the area. By integrating stress tensor solutions with strain data, we aim to assess the tectonic processes governing deformation and fault activity in this slow-deforming region. Also, through InSAR time-series analysis, we attempt to detect the active faults within the slow-deforming area. Another important objective is how the rapidly deforming NAT and the Mygdonian basin control or influence the slower deformation processes that occur in East Macedonia and Thrace. This approach will enhance our understanding of the region's geodynamics and contribute towards future seismic hazard assessments in the region such as the work planned in EU project COREU (https://coreu.eu/).

## AS25-1019

# A zoning model for seismic hazard analysis of Finland and adjacent areas: A fusion of seismological and geological data

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We present a new seismic zoning model with three hierarchical levels of details (macro-, meso- and microlevel) for Finland and adjacent areas in northern Europe for seismic hazard mapping. We have delineated area seismic source zones (SSZ) by fusing seismological, geological, and geophysical data, and tectonic boundaries. The target region, mostly situated in the stable Fennoscandian Shield, predominantly exhibits earthquakes below moment magnitude 3. A certain persistence of the distribution of the enhanced seismicity belts is observed in the region throughout the catalog's span of five centuries. The spatial variation of seismicity is expected to reflect changes in the local stress field, and the changes favor preexisting zones of weakness. The zoning model relies on the idea that weakness zones that formed during ancient geological episodes remain present in the crust, and the current stress field can be released along such zones. For example, most of the late-glacial or post-glacial faults are situated parallel to and in proximity of ancient deformation zones, or even coincide with them. Using lithotectonic units as geological foundation of the model emphasizes orogenic folding and faulting as a source of weakness zones. We have used well-defined boundaries, such as the Ladoga-Bothnian Bay Deformation Zone (the Archean-Paleoproterozoic boundary), geological province lithotectonic boundaries, and well-defined deformation zones, when augmenting limited to non-existent seismicity data with geology. As the tectonic boundaries could be a potential source of seismicity, they have been included within the SSZs. This has resulted in SSZs that are structurally non-uniform in the border areas.

## AS25-1046

# The evidence of EARS southern African extension from seismotectonics of 2017 Moiyabana, Botswana earthquake

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The 3 April 2017 $M_W$ 6.5, Moiyabana earthquake occurred in the continental interior of the African plate and region previously considered stable. The mainshock and aftershock sequences were analysed based on a local seismic network. The earthquake rupture geometry is constrained with more than 1,000 aftershocks recorded over three months and from the InSAR analysis of Sentinel-1 images (ascending orbit). More than 500 aftershocks of magnitude $M \geq 0.8$ were recorded in April 2017 including the largest aftershock. Focal mechanism solutions of the mainshock and aftershocks display a predominance of NW-SE trending and NE dipping normal faulting. Stress inversion of focal mechanisms obtained from the mainshock, and aftershock database are compatible with a NE-SW extension under normal faulting regime. The InSAR study shows fringes with two lobes with 4 to 6 cm coseismic slip on an NW-SE elongated and 30-km-long surface deformation consistent with the mainshock location and normal faulting mechanism. The modelling of surface deformation provides the earthquake rupture dimension at depth with ~ 1 m maximum slip on a fault plane striking 315°, dipping 45°, -80° rake and with Mo 7.12 1018 Nm. Although the seismic strain rate is low, the occurrence of the 2017 Moiyabana earthquake, followed by an aftershock sequence in the central Limpopo belt classifies the intraplate region as an active plate interior. We demonstrate a graben structure modelled from the mainshock, and aftershock sequence and the extensional stress regime associated with the Moiyabana earthquake, as the extension of the EARS in southern Africa.

## AS25-1088

# Source and path spectral parameters in the Tagus Valley region and South of Portugal

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Source and path spectral parameters are essential for finite fault stochastic models, which allow simulating intense ground motion movements in regions with moderate seismic activity. The purpose of this work is to determine the *kappa* parameter, corner frequency and stress drop for the area around Tagus Valley and South of Portugal, two regions with significant seismic risk. Source spectra were first obtained for the records of the Portuguese seismic network, for both horizontal components. In a first approach, *kappa* parameter was determined by fitting the high-frequency decay of the acceleration spectrum with a straight line, in a log-linear scale. Corner frequency was determined by the half square root of the ratio between the velocity source spectra integral and displacement source spectra integral. Stress drop was determined correlating corner frequency and seismic moment, considering the ω-square model established by Brune (1970). On a second alternative approach, the SourceSpec package was also used to compare and validate results. *Kappa* parameter was estimated to be k = (0.031±0.015)s for the Tagus Valley region and k = (0.028±0.021)s for the South of Portugal. Stress drop estimates range between 0.1 MPa and 90 MPa for the events in the Tagus Valley, for the South of Portugal stress drop estimates range between 0.01 MPa and 300 MPa. The determined parameters will allow the application of the stochastic model and thus simulate the intense seismic movements, either through time series or through their spectral content and contribute to seismic risk assessment.

## AS25-1141

# Active tectonic deformation along the passive continental margin of northwestern Australia

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The northwestern edge of the Australian continent is a passive tectonic margin. Although strain rates on this margin are low, with motions below the threshold of geodetic detection, crustal deformation is occurring between 9°–27° S. Seismic reflection interpretation, seafloor and onshore geomorphic mapping, fluvial geomorphologic analysis, and seismological and paleoseismological studies have been used to evaluate deformation occurring along the continental margin. The results of these investigations document the following processes which extend up to 2,000 km from the northern plate boundary: (1) broad-scale down warping of the continental shelf in the north evidenced by subsidence and submergence of MIS Stage 5 atolls and Stage 6 low-stand estuary systems; (2) dominantly dextral strike-slip fault reactivation along the 2,000 km-long Western Australia Shear Zone that extends from Bonaparte Basin in the north to the Murchison region in the south; (3) emergence of coastal marine terraces along the Cape Range; (4) fold growth affecting channel morphology along the Gascoyne River; and (5), stream capture and impoundment of Lake Wooleen along the late Quaternary Roderick River fault scarp.

Deformation in this low strain region is inferred to be driven by a transition in plate boundary architecture. North-directed subduction of Indian oceanic crust is occurring along the Java trench (west of 120° E) while south-directed obduction of Miocene to recent foreland deposits onto the Australian continental lithosphere is occurring along the Banda Arc (east of 120° E). This change in subduction polarity is reactivating former passive margin structures across the North West Shelf and northwestern continental Australia.

## AS25-1183

# The 2024 Update of the Earthquake Model for the Middle East (EMME24): A Community-Driven Seismic Hazard Assessment

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The 2024 update of the Earthquake Model of the Middle East (EMME24) represents the latest advancement in regional-scale probabilistic seismic hazard assessment, spanning a region between the Eastern Mediterranean and the Himalayas. Notably, EMME24 is a truly community-driven hazard model, built upon the in-kind contributions of regional experts, incorporating the latest earthquake, geological, and ground motion data, alongside refined methodologies, to provide a uniform and cross-border evaluation of ground-shaking hazards. EMME24 integrates a newly developed seismogenic source model with a suite of alternative ground motion models within a novel backbone logic tree framework, implemented using OpenQuake (Pagani et al., 2014). This contribution presents the key results of EMME24, including insights gained from the impact of various modeling assumptions on regional hazard estimates. EMME24 represents a substantial advancement over EMME14 and will serve as the new reference for seismic hazard in the region, directly informing future risk modeling and regional disaster mitigation actions.

## AS25-1187

# Impact of 3D fault geometry on surface rupture probabilities using earthquake cycle simulations: A case study in central Italy

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Surface ruptures caused by earthquakes can have devastating impacts on critical infrastructure, such as bridges, tunnels, pipelines, and dams. The risk posed by surface fault ruptures is well recognized in international guidelines. Quantifying surface rupture probabilities is a key objective in probabilistic fault displacement hazard analyses (PFDHA). However, a significant challenge, especially in regions with slower deformation, is the scarcity of surface rupture records, which limits statistical analyses and forecasting accuracy.

This study employs a novel method to estimate surface rupture probabilities using simulated earthquake ruptures from the RSQSim earthquake cycle simulator, focusing on the Monte Vettore Fault System in central Italy. After calibrating rate-and-state parameters to match empirical relationships, we create 100,000-year-long earthquake catalogs using twelve distinct 3D fault geometry models. These models incorporate different fault dip configurations—constant and listric—as well as variations in segment connectivity at depth and roughness, ranging from fully planar to surface-trace roughness. High-resolution fault discretization (approximately 300 m elements) ensures a detailed representation of fault complexity.

We assess how these geometries influence surface rupture probabilities and compare the simulated cumulative throw and earthquake recurrence intervals with geomorphic and geological records. Additionally, we compare our results against empirical regressions of rupture probabilities. Our findings demonstrate the potential of earthquake cycle simulations to refine PFDHA, offering insights into the long-term behavior of complex fault systems and their likelihood of surface rupture.

## AS25-1189

# Seismic hazard assessment in Stable Continental Regions: new seismotectonic models for metropolitan France

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Seismotectonic zoning is a fundamental component of seismic hazard assessment. It defines regions where earthquake characteristics, such as frequency-magnitude relationships, are assumed to be homogeneous, primarily based on local active tectonic features.

However, in Stable Continental Regions, where deformation and seismicity rates are very low, seismotectonic zoning remains challenging due to the scarcity of data.

In this study, we develop new seismotectonic models for metropolitan France and neighboring regions of intraplate Western Europe, taking advantage of the significant increase in data collected in recent years. These models will be used for source characterization in the new probabilistic seismic hazard assessment (PSHA) for metropolitan France.

We consider traditional datasets, such as instrumental and historical earthquake catalogs and crustal structure information, as well as alternative data that are not usually considered in intraplate settings. Geodetic (GNSS) strain rates from various solutions help identify zones of coherent deformation and tectonic styles. Additionally, since present-day seismicity is not solely driven by plate tectonics, we incorporate geodynamic models accounting for glacial isostatic adjustment (Weichselian-Würm Glaciation) and isostatic responses to Quaternary-Holocene erosion and sedimentation.

These datasets and models allow us to distinguish zones of well-defined tectonic styles and rates (e.g., the Pyrenees) from areas where deformation and seismicity are less well constrained or where datasets suggest divergent interpretations.

Our study highlights the challenges of quantifying seismic hazard in low-strain regions and the complexity of present-day tectonic and geodynamic processes in metropolitan France, where surface processes may play an important role.

## AS25-1206

# A unified earthquake catalogue for the 2024 update of the Earthquake Model of the Middle East (EMME24)

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A harmonized earthquake catalogue is fundamental to seismic hazard assessment, providing the basis for analyzing seismicity patterns and estimating earthquake occurrence rates. As part of the 2024 update of the Earthquake Model of the Middle East (EMME24), we refined and expanded the earthquake catalogue through collaboration with local and international experts. This update extends the original EMME14 catalogue by incorporating instrumental earthquakes recorded between January 1, 2007, and December 31, 2023. Special emphasis was placed on the 1900–1970 period by integrating data from the newly released ISC-GEM v11 catalogue. The catalogue was systematically curated and homogenized, involving the identification and resolution of duplicate events and a thorough review of discrepancies for moment magnitude and depth distributions. All magnitudes were converted to the moment magnitude (Mw) scale, resulting in a final dataset of over 75,000 earthquakes with magnitudes greater than 3.5. The catalogue underwent statistical completeness analysis and was processed with declustering algorithms to enhance its reliability for seismic hazard assessment. Here, we outline the key processing steps used to develop the unified earthquake catalogue and present insights from its statistical analysis, emphasizing its importance for earthquake rate forecasting in the Middle East.

## AS25-1254

# Where faults hide: an alternative structural style of deformation for an enigmatic slow-deforming zone of the central-southern Apennines (Italy)

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The mechanical properties of sedimentary layers, particularly the competence contrast between adjacent strata, can strongly influence deformation patterns and mechanics of faulting. As a result, searching for geomorphological and structural evidence of recent tectonics can be challenging in peculiar structural-geological settings characterized by repeated variations in rock strength (e.g., limestones/marls alternance) and low deformation rates.

This study focuses on the central-southern sector of the seismically-active Apennines, across the Abruzzo and Molise regions boundary (AMB), where surface faulting changes dramatically its geomorphic signals, while geodetic deformation and long-term tectonics suggest continuity with the adjacent sectors. The stratigraphy of the uppermost crustal layer consists of ~200 m-thick competent deep carbonate slope deposits sandwiched between foredeep turbidite sequence on top and a basinal, predominantly clayey-marly succession below. Subsurface data from hydrocarbons exploration also show that turbidites and clays successions reach up to 2.5 km in thickness and unconformably overlay an up to 6000 m-thick buried carbonate platform.

We explore the hypothesis that this setting may have played a role in the up-dip propagation of normal faults rooted in the buried carbonates and that even multiple slip events over the Late Quaternary may not manifest through clear geomorphic signatures on the surface.

By integrating morphometry from high-resolution topography, aerial-photo interpretation, field mapping and subsurface data, we investigate the relationship between (subtle) surface deformation and structures reconstructed at depth. Together with stratigraphic and rheologic observations, we propose a peculiar deformation style for this region, highlighting the seismic potential of incipient or buried active normal faults.

## AS25-1290

# Seismic hazard assessment in the Central Apennines: investigating single and multi-fault rupture scenarios

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The Central Apennines is among the most seismically active regions in Europe, having experienced multiple moderate-to-high magnitude seismic sequences, including the L'Aquila 2009 and Central Italy 2016 earthquakes. This region benefits from an extensive dataset derived from geological, seismological, and paleoseismological studies, as well as a comprehensive historical earthquake catalog (CPTI15, Rovida et al., 2022), all of which are fundamental for Probabilistic Seismic Hazard Assessment (PSHA). In this study, we develop a fault-based earthquake recurrence model to characterize the long-term behavior of seismogenic faults. Initially, we consider each fault section as an independent seismic source, assigning either a characteristic rupture behavior, where an earthquake occurs by rupturing the entire fault surface, or a floating rupture behavior, where only a section of the fault is activated (Akinci et al., 2009). To further analyze rupture scenarios, we evaluate all possible fault section combinations, considering magnitudes up to the maximum expected earthquake. We investigate the potential for multi-segment ruptures, where adjacent faults may rupture together based on their geometric and kinematic compatibility. These multi-fault rupture scenarios are essential for understanding how large earthquakes propagate within complex fault systems and their impact on seismic hazard assessment. Finally, we derive probabilistic seismic hazard levels by integrating our fault rupture models with a set of ground motion models employing the OpenQuake engine (Pagani et al., 2014). To validate our approach, we compare the resulting earthquake forecasts with the available seismic catalog at a regional scale, providing insights into the accuracy and reliability of our seismic hazard assessment.

## AS25-1316

# Current state of practice in hazard modeling at GEM and future directions

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The Global Earthquake Model (GEM) Foundation's hazard team maintains a mosaic of models to assess seismic hazard worldwide. This collection integrates publicly available models developed by national agencies and international projects with hazard models created by the GEM hazard team.

Most of GEM's models cover broad territories, spanning multiple nations. They are created using a combination of methodologies that align with recent scientific advancements and aim to address deficiencies and gaps identified in previous projects.

Current practices for developing seismic source characterization at GEM depend on historical seismicity, global navigation satellite systems data, and geodynamic modeling. We select ground-motion models utilizing standard preselection criteria, residual analysis, and techniques to evaluate the performance of pre-selected ground-motion models. Epistemic uncertainty is represented either through a multi-model or a backbone approach.

In this communication, we will illustrate the available methods used to create earthquake sources in different tectonic regions and to construct ground-motion characterizations; we will discuss the advantages and limitations of these methods and current developments along with future directions.

## AS25-1354

# Present-day seismicity and active faulting in the Hoggar swell, (Central Sahara, Algeria), case of intraplate earthquakes

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The Hoggar shield is a broad (1000 km$^2$) area of Precambrian basement with Quaternary volcanism and background seismicity. Geological and Geophysical investigations were performed over the Hoggar region to better understand its inner structure and the related Neogene-Quaternary volcanic and present-day seismic activity. We refer to the unique seismic tomography in the area (Hoggar shield) that concluded to the presence of volume with hot material (large thermal anomaly zone) extending down to the lithosphere under the central Hoggar. Evidence of neotectonic activity is observed on the meridional shear zones and along the Oued Amdad volcanic area in the Serouanout Cretaceous sedimentary basin (eastern Hoggar). The region is characterized by diverse faulting mechanisms including normal, thrust and strike-slip faults that affect Neogene and Quaternary units. Tectonicanalysis shows an extensive network of normal faulting affecting the Neogene-Quaternary sedimentary formations and the volcanic rocks spreading over the central part of the Hoggar region. The distribution of normal faulting seems to be related to the post-volcanic tectonic activity, during the Miocene to Quaternary time span. Although the background seismicity is of low-level, the focal mechanism solution of the 14 February 2013 earthquake (Mw 4.4, 6 km depth) shows a normal faulting mechanism with NW-SE trending faults. The crustal tomography and fault network structures are supported by gravity anomalies. The large low-density anomaly was attributed to the melting at the lithosphere/asthenosphere interface beneath the central Hoggar.

## AS25-1381

# Seismic wave propagation in the Sulmona basin: effects of 3D geometry and infill properties

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The central Apennine thrust-and-fold belt is characterized by NW-SE oriented ridges interspersed with intramountain basins. This low-to-moderate strain rate region experiences regional uplift and active extension, with seismic activity primarily occurring along NW-SE normal faults. As one of the most seismically hazardous areas in Italy, it has been the focus of numerous studies on active fault systems and site effects. However, data-driven 3D geological models of seismically susceptible basins remain scarce, and research on seismic wave propagation within these complex subsurface structures is still limited. Previous studies have investigated the effects of past earthquakes, such as L'Aquila (2009) and Norcia (2016), through scenario simulations incorporating variations in slip distribution, magnitude, and structural parameters.

This study presents a 3D numerical assessment of seismic wave propagation and site effects in the Sulmona Basin, a key intramountain basin in the central Apennines. The model integrates a high-resolution reconstruction of Plio-Quaternary lithologic units, incorporating basin geometry, depositional sequences, and their mechanical properties. We analyze the influence of these parameters on surface-recorded ground shaking spectra, evaluating seismic response variations under different model conditions.

To further assess seismic hazard, we simulate an ensemble of realistic earthquake scenarios with varying magnitudes and slip distributions. The numerical simulations, performed using the open-source spectral-element method code SPECFEM, provide insights into basin-induced amplification effects and spatially variable ground motion patterns. The results contribute to refining seismic hazard assessments in the Sulmona region, highlighting the critical role of basin structure and subsurface heterogeneity in shaping local shaking intensities.

## AS25-1398

# Ongoing research in Plio-Quaternary deformation and reactivated inherited structures with seismogenic potential in Southwest Iberia, Portugal

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The Southwest of Portugal (SW-PT), is the Portuguese inland region closest to the European-African plate boundary, and to Mw≥ 8 1755 epicenter. This area has Quaternary crustal deformation, recognized through several faults generally trending NNE-SSW, and poorly preserved Quaternary marine terraces uplifted at higher rates than remaining southern Portugal, suggesting that this area corresponds to a "block" behaving differently.

Recent geophysical surveys highlighted a positive gravimetric anomaly, suggesting crustal thinning consistent with the uplifted area. Additionally, geodetic surveys corroborated this area to be limited inland by an unknown 90 km NW-SE strike-slip structure, that matches an active fault for ~40 km, corresponding the remaining ~50 km to an inherent structure not recognized as an active fault, despite a noticeable and prominent scarp in the landscape. These observations unveiled a complicated and previously unknown regional tectonic framework, that includes inherited and reactivated structures.

Ongoing studies are focused on filling gaps of knowledge in the SW-PT and are aimed at identifying evidence for Quaternary deformation along inherited structures. Furthermore, we will investigate the reactivation of fault zones by applying a combination of geochronology methods, namely Luminescence (OSL) and Electron Spin Resonance (ESR). Results should contribute to characterizing Quaternary seismicity and understanding spatial and temporal relationships between regional structures (inland and offshore), and consequently to improve the regional seismic hazard.

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## AS25-1455

# Modernization of Russian building codes and construction seismic zonation maps in peak accelerations accounting for regional source and path effects

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Currently, the building codes in Russia do not respond the level of world seismology and need to be seriously updated. During the update, we are planning to preserve the progressive techniques developed in the previous years and replace outdated approaches. Russia has a large territory, including regions with different levels of seismic activity and types of seismicity, but a rare network of seismic observations (~450 seismic stations). In various parts of the country, subduction-type, crustal, and stable continental-plate earthquakes occur, and propagation path parameters also vary from region to region.

To account for these differences, we divide the country into 8 large regions with quite homogeneous characteristics, and estimate source and path parameters in each region based on stochastic simulation of records of local earthquakes. Then, we apply stochastic simulation again to construct sets of acceleration time histories in wide ranges of magnitudes and distances; based on these data, we develop ground motion prediction equations and construct seismic hazard maps in peak acceleration units and response spectra.

We have obtained and present the results for the Baikal Rift zone and the Caucasus (regions of crustal seismicity), the Kola Peninsula and Karelia (stable continental seismicity), and the Urals – the region of transitional seismicity.

## S16 Imaging seismic discontinuities in the mantle - from the mantle transition zone to D”

### AS25-0055

# Enhancing mantle scattering resolution – addressing crustal effects

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The subducting oceanic plates (slabs) play a crucial role in recycling crust and lithospheric material into the deep mantle. However, the depth to which these materials penetrate varies significantly. While tomographic models show some slabs extending all the way to the core-mantle boundary, others stall at different depths (660 km, 1000 km, 1200 km). The factors influencing this variability remain unclear. This study investigates this phenomenon by examining scattered waves to identify small-scale localized structures, e.g., basaltic oceanic crust, which are below the resolution of tomography studies. We employ array techniques to detect potential mantle scatterers associated with slabs, using both temporary and permanent seismic arrays in Alaska. By utilizing the F-statistic coherence method, we amplify signals off the great-circle path of the earthquake backazimuth, tracing seismic energy otherwise difficult to observe. Our observations reveal consistent offsets in backazimuth and slowness from expected values across many sub-arrays. Notably, a 5° variation in picked backazimuth could result in up to a 500 km discrepancy in scatterer location, significantly affecting interpretation. We systematically quantify the offsets and observe spatial patterns correlating with crustal structures, thus suggesting receiver side structure could affect beamforming and the located slab position. Our findings provide insights into the influence of receiver-side structures on beamforming, enhancing the accuracy of slab location interpretations and improving our understanding of mantle dynamics.

## AS25-0193

# Heterogenous structure near the base of the mantle transition zone beneath the northern Japan Sea

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Below the northeastern edge of China, double seismic discontinuities near the base of the mantle transition zone (MTZ) were indicated by the receiver function studies (Niu and Kawakatsu, 1996; Sun et al., 2020). The present study examines heterogeneous structure near the base of MTZ beneath the northern Japan Sea, which is located to the east of the previously detected double discontinuities towards the trench.

We first examine P waves triplicated at depths of around 660 km. A clear triplication of P wave appears in Japanese waveform data in a similar manner to iasp91. In addition, signals following the triplication are observed, which appear to be the manifestation of another triplication. The signals are not limited in particularly local areas, and their small apparent slowness suggests that the signals can be refracted below the 660 discontinuity.

It is, on the other hand, not obvious whether the later arriving signals are caused by discontinuities or scattering. Assuming that they are caused by seismic scattering, we also characterize the structure by means of the Kirchhoff migration. In the distance range where we observe the later signal at each station and iasp91 predicts the initial arrivals of P wave at almost constant apparent velocity, we perform the Kirchhoff migration for hypothetical scattering points, obtaining large values at the points which match the arrival times of the later signals. We compare the results in different distance ranges and discuss the structure.

## AS25-0273

# Probing mantle heterogeneity beneath the central Mediterranean: insights from P receiver functions

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The central Mediterranean provide an ideal setting to investigate slab-mantle interactions. Seismic tomography has revealed the presence of subducted lithosphere in the upper mantle, including the Dinaric-Hellenic and Calabrian slabs, as well as a stagnant slab at the base of the Mantle Transition Zone (MTZ). Additionally, evidence of mantle upwellings further complicates the region’s geodynamics. We aim to assess the impact of subduction and mantle upwellings on the MTZ, which is governed by phase transitions in mantle minerals at approximately 410 km and 660 km depth. These discontinuities are sensitive to thermal and compositional variations, making them key indicators of mantle dynamics. Variations in their depth and properties reflect interactions between descending slabs and rising material. The nature of MTZ discontinuities, in turn, plays a crucial role in regulating mantle convection, either impeding or facilitating material exchange at both regional and global scales.

We analyze upper mantle discontinuities beneath the Adria and Calabrian Arc regions, and in the northwestern Tyrrhenian basin, using P receiver functions (RFs). We assess waveform complexities at key mantle boundaries by stacking RFs in back-azimuth sectors and applying moveout corrections across multiple frequency bands.

Our results reveal significant depth variations in the 410 km and 660 km discontinuities, with localized depressions exceeding 30 km at the 660 km interface, suggesting anomalous thermal conditions or phase transitions in majorite-garnet at the base of the MTZ. Additionally, a discontinuity detected at ~300 km depth may indicate compositional heterogeneity, providing further evidence of mantle heterogeneities linked to subduction and upwelling processes.

## AS25-0328

# Sdiff and Pdiff Postcursors related to the Basal Structure of the Hawaiian Mantle Plume

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Ultra-Low Velocity Zones (ULVZs) are mysterious seismically slow patches on the core-mantle boundary observed by various seismic phases. The Hawaiian ULVZ is one of the best studied ULVZs as it is sampled well from earthquakes in the western Pacific to arrays across North America.

Here we show evidence of Sdiff postcursors which are refracted and delayed by the Hawaiian ULVZ (Cottaar & Romanowicz 2012, Martin et al, 2023b). Postcursors in a period band of 10–20 s are delayed by 20 to 40 seconds. There is a second set of postcursors in the 3–6 s period band with much longer delay (Li et al. 2022). Beamforming shows they both come from the same area, indicating layering within the Hawaiian ULVZ with a strongly reduced basal layer of several kilometers.

Joint observations on their S and P wave velocity reductions could help constrain the nature of ULVZs, through interpretation of observed dVp:dVs ratios. We hunt for Pdiff postcursors, but only find potential observations at periods around 1 s. Stacking shows that the Pdiff this energy comes from the same region, corresponding to a dVp:dVs ratio of ~1–2 and supports an iron enrichment hypothesis. However, while the Sdiff postcursors show typical slownesses for diffracted waves, Pdiff postcursors show slownesses that are 15% higher, which are typically related to scatterers coming from several 100s of kms above the CMB. Potentially this energy comes instead from strong scatterers within the mantle plume above the Hawaiian ULVZ, indicating potentially entrained heterogeneity.

## AS25-0471

# Unknown phase in SS precursor: S1000S or PPS

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The widespread detection of underside reflections from PP and SS waves at approximately 1000 km depth (precursor phases: P1000P and S1000S) suggests the presence of a seismic discontinuity in the lower mantle near this depth. However, previous investigations of this feature using SS precursors have reported a wide range of reflection depths in different study regions—spanning from about 800 to 1300 km—implying that the S-wave reflections may arise from regional structures rather than a globally continuous interface.

Here, using data from the densely deployed USArray and the China National Seismic Network (CNSN), we carefully re-examine the slowness, travel times, and particle motions of the “S1000S” phase recorded on transverse components in different regions. Our analysis indicates that the apparent large variations in reflection depth can be explained by misidentification of PPS or PPPS phases, which have travel times similar to S-wave reflections but exhibit slightly smaller slowness in the distance range of 100° to 135°. In contrast to SS precursors, which are frequently observed on transverse components, PPS phases typically appear only on the radial and vertical components.

We then explore two possible mechanisms that could generate transverse-component PPS arrivals: (1) upper mantle anisotropy and (2) out-of-plane propagation caused by large velocity structures (subducted slab or upwelling plume). Using 2D and 3D synthetic tests on two types of models, we confirm that both mechanisms can account for the unexpected presence of PPS arrivals on transverse records, supporting our explanation for these observations.

## AS25-0556

# A global map of ultra-low velocity zones using postcursors to S diffracted waves

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Ultra-Low Velocity Zones (ULVZs) are regions of greatly reduced wavespeed that lie on the core-mantle boundary (CMB), with lateral and vertical length scales of 100s of km and 10s of km respectively. As well as influencing CMB heat flux and potentially being linked to the two Large Low Shear Velocity Provinces (LLSVPs), they may also play a role in whole mantle dynamics; as passive tracers or more actively feeding into or anchoring plume hotspots. The nature of their composition and origin remains uncertain, with iron-enrichment or partial melting being two possible explanations. Knowledge of the global distribution of ULVZs, both where they are and where they are not, would allow for their relationship with LLSVPs and hotspots to be probed further.

Previous studies have made a global compilation based on studies using heterogeneous data types (Yu & Garnero, 2018) or algorithmically modelled anomalous SPdKS waveforms (Thorne et al., 2021) to maximise coverage. In this study, we use postcursory energy to the shear diffracted wave, Sdiff. This phase has previously been used to locate and model ULVZs, and the extended diffracted portion of this phase on the CMB makes it particularly well-suited to studying large areas of the core-mantle boundary.

Our study presents a global map of where ULVZs are present or lacking using a large handpicked Sdiff postcursor dataset comprised of over 4 million traces. This dataset has then been used to statistically test the spatial relationships between ULVZs and both LLSVPs and surface hotspots.

## AS25-0598

# Slab-plume interactions in the mantle transition zone: high-resolution SS precursor imaging of western Pacific subduction and Iceland plume systems

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The mantle transition zone (MTZ) plays a vital role in mediating the material and energy transfer between the upper and lower mantle. Although SS precursor studies effectively resolve global MTZ structures at spherical harmonic degree-20 (~2000 km resolution), regional models exhibit significant inconsistencies, primarily due to broad Fresnel zones of SS precursors and methodological differences in data processing. This study investigates the MTZ structure in two end-member geodynamic settings of western Pacific subduction zone and Iceland plume, utilizing a unified processing workflow. A novel multi-dimensional reconstruction method is applied to an extensive SS precursor dataset (1976–2023), enabling a robust comparison at sub-thousand-kilometer scales.

The MTZ beneath the western Pacific averages 250 km in thickness, which is about 12 km thicker than that beneath the Iceland region (238 km). Both regions exhibit localized thinning beneath the volcanic zones: ~240 km below Changbai area and ~230 km beneath Iceland. The Changbai anomaly aligns with a low-velocity zone embedded within the high-velocity Pacific slab, suggesting mantle upwelling through a gap within the stagnated slab. The Iceland’s thinning coincides well with a vertically continuous velocity structure, consistent with a deep-rooted mantle plume penetrating the MTZ to supply Mid-Atlantic Ridge hotspots. These contrasting features demonstrate how the MTZ interacts with both slab- and plume-driven processes. Our approach highlights the potential of advanced processing techniques to overcome traditional resolution limits, offering new insights into complex mantle dynamics.

## AS25-0669

# Localized low-shear-velocity zones in the D” Layer beneath the Tibetan Plateau and adjacent regions

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We investigated the detailed shear velocity structure of the D″ layer beneath the Tibetan Plateau and adjacent regions using S and ScS travel time residuals from waveforms recorded by the dense China Digital Seismic Network. The data were derived from shallow earthquakes (Mw ≥ 5.6) occurred in the Eastern Europe and Central Asia. The seismic waveforms were modeled using specfem3d_globe synthetics based on CRUST1.0 for the crust, S40RTS for the mantle, and AK135 for the lowermost 300 km of the mantle. Differential travel time residuals for S and ScS phases were obtained through waveform cross-correlation between the observed and 3-D synthetic data. Our results reveal dominant high-velocity anomalies in the D″, consistent with prior tomography studies. Importantly, we identified two distinct localized low-shear-velocity zones (~5° extent) embedded within these high-velocity regions. These low-shear-velocity anomalies likely reflect thermochemical heterogeneities or partial melting associated with subducted Tethyan or Pacific slab materials. This finding provides new insights into the complex dynamics of the D″ layer.

## AS25-0697

# On the use of seismic discontinuities to infer temperature and composition of the upper mantle and transition zone

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P-to-s and S-to-p converted waves are teleseismic P (or S) waves that convert part of their energy into S (or P) waves when encountering a discontinuity in material properties. These converted waves carry significant information about the seismic structure beneath the receiver. In particular, P-to-s waves converted at the 410- and 660-km discontinuities can be used to map variations in the sharpness and depth range of velocity gradients in the mantle transition zone. Here, we present a strategy for determining mantle composition and thermal structure directly from the inversion of P-to-s and S-to-p converted waves. This approach utilises self-consistent mineral phase equilibria calculations to incorporate plausible petrological knowledge of seismic discontinuities into the geophysical inversion, optimising profiles of physical properties (e.g., bulk modulus, shear modulus, and density) to match the observed data. Finally, we demonstrate the potential of this technique through global and continental-scale applications and discuss its limitations and future directions.

## AS25-0742

# Investigating the structure and mineralogy of D’’ with reflected waves beneath the Indian Ocean

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The D″ layer overlies the Core-Mantle-Boundary (CMB) and is the lower thermal boundary layer of the mantle. It is approximately 300 km thick and plays an important role in the dynamics of the deep Earth. Furthermore it exhibits complex structural, thermal, and mineralogical properties that have not been fully characterized. These physical properties significantly influence heat transport between the Earth’s core and mantle, thereby affecting both the dynamics of the outer core and the generation of the geomagnetic field. The objective of this study is to improve our understanding of the mineralogical composition and seismic velocities of the D″ layer beneath the Indian Ocean, and examine potential correlations with Earth’s magnetic field.

In this study we analyse seismic data using array methods (vespagram analysis, slowness-backazimuth analysis) to investigate structure and mineralogy of the D″ layer. We examine P- and S-wave reflections at the D″ discontinuity and compare them with P, PcP, S, and ScS phases. We use data from earthquakes in Indonesia as recorded by seismometers in East Africa. We test two main theories regarding the cause of the D″ discontinuity: (1) subducted harzburgite with a phase transition from bridgmanite to post-perovskite, or (2) an accumulation of subducted mid-ocean ridge basalt (MORB). In the first scenario, anisotropy is expected, while in the second, a higher SiO2 content would lead to increased seismic velocities.

## AS25-0751

# Seismic anisotropy due to textures above and below the 410 km discontinuity

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We investigate the effect of various geodynamic contexts on the reflection coefficients of P and S waves underside reflections off the 410 km discontinuity, to detect seismic anisotropy at this boundary layer due to textures above and below the 410 discontinuity. We calculate anisotropic reflection coefficients for P and SH underside reflections using elastic tensors resulting from aligned minerals above and below the 410 km discontinuity for different deformation scenarios. Our results indicate differences in amplitude and polarity patterns of reflection coefficients for different deformation geometries in the case of an anisotropic olivine layer above an anisotropic wadsleyite layer, compared to the case of anisotropic olivine above an isotropic wadsleyite layer. We find that the amplitudes of P and SH precursors are influenced by the azimuth and angle of incidence, and polarity reversal are observed for some deformation styles, offering a diagnostic tool for discriminating among scenarios. Furthermore, in some cases water content of wadsleyite plays a role in creating the polarity reversal of the waves compared to the case of dry wadsleyite.

## AS25-0898

# Testing the consistency of D’’ reflected waves under Siberia and Canada for different crossing paths

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In recent geomagnetic field models, patches of intense magnetic flux can be identified. The north magnetic field is characterized by two such flux lobes, one underneath Canada and one underneath Siberia, known as High Latitude Flux Lobes (HLFL). A third HLFL is postulated underneath the Norther Atlantic but has not been observed. Studies show that the lower mantle influences the magnetic field through the control of the geodynamo. The aim of this study is to investigate how the underlying lower mantle structure and mineralogy may influence these regions of high magnetic signature. Using array methods, we search for D” reflected PdP and SdS waves which arrive as precursors to the core-reflected PcP and ScS waves, and that sample the lowermost mantle beneath Siberia and Canada, with a number of intersecting paths. Especially the new Alaskan station (TA) deployment allows for a better number of crossing paths that are needed to establish whether anisotropy is present. Vespagram and slowness-backazimuth analysis are carried out to detect the presence of lower mantle reflectors at the top of the D” and establish the wave’s travel direction (in plane versus out-of-plane). A comparison with synthetic seismograms establishes whether the observations can be explained by a previously suggested 300 km thick D” layer. We present a number of observations in these two regions and a wider coverage than previously possible by showing the results for PdP and SdS waves, their travel time and polarity measurements for different crossing paths and focus on the consistency of the observations.

## AS25-0916

# Effects of mineral phase transitions on flow dynamics and structure of the lowermost mantle

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Numerical models of mantle convection are a useful tool for constraining the thermal evolution of the Earth. Among other things, they may be used to predict the distribution of thermal anomalies arising due to ponding subducted slabs and hot upwellings forming atop the core mantle boundary (CMB), which may be considered as a proxy for the heat flux from the core into the mantle.

We explore joint effects of mineral phase transitions and rheological characteristics on flow evolution and structure in the lowermost mantle, which are not yet well constrained to date, using global mantle circulation models. To this end, we employ thermodynamic mineralogical models to inform our geodynamic simulations on material behaviour at runtime. The lowermost mantle structure is characterised by the exothermic bridgmanite=post-perovskite transition. Lateral temperature variations above the CMB lead to strong topographic undulations of the transition, which shows deflections of more than 100 km towards shallower and greater depths. This topography results in lateral variations in buoyancy, enhancing the flow of rising plumes into the mantle and trapping slabs above the CMB. We find the strength of this effect to be strongly dependent on bulk composition and viscosity structure. Moreover, the morphology and distribution of downwellings and plumes is strongly affected by both mineral phase effects and mantle rheology. We specifically highlight the importance of self-consistently testing geodynamic models of mantle flow against seismic observations in order to better constrain the characteristic structure and behaviour of the lowermost mantle.

## AS25-1039

# Seismic evidence for a thin rigid zone at the top of the core beneath north central Asia

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Clear PcP waves are recorded by a dense nodal array in northeast China from an intermediate depth earthquake in Hindu Kush. The nodal array comprises two linear subarrays, each housing 200 nodal sensors spaced at intervals of 0.5 km. A later arrival is observed after PcP at frequency higher than 1 Hz. Numerical modeling indicates that the later arrival can be best explained by a reflected S wave in a thin rigid layer at the top of core. Such a thin rigid zone was first observed beneath Southwest Pacific and referred to as core rigid zone (CRZ). We found that the best CRZ model has a thickness of 0.2 km with an S-wave velocity of 0.6 km/s, and a lateral extension of tens of kilometers. The small but nontrivial S-wave velocity suggests that the zone has composition of molten iron mixed with solid materials, likely saturated light elements, which act as light sediments being trapped in dome-shaped structure beneath the mantle. The presence of the CRZ at the top of the outer core could offer new insights about the fate of light elements inside the outer core.

## AS25-1436

# Imaging the mantle with earthquake reflection seismology

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Seismic imaging of Earth’s deep interior has traditionally relied on transmitted waves, with tomography and converted-phase studies providing accurate but often limited-resolution constraints. Reflection seismology, widely used in exploration geophysics, remains largely underutilized for imaging mantle structures due to the scarcity of controlled sources with sufficient power for that purpose. Here, we discuss earthquake reflection seismology (ERS) as an approach that employs earthquake-generated specular reflections to provide new geophysical information on the deep Earth structure.

We outline the theoretical framework of ERS and discuss its potential for mapping mantle discontinuities, including the 410 km and 660 km phase transitions, as well as fine-scale structure at the D” and the Core-Mantle Boundary (CMB). The main challenges of the technique are examined, particularly the weak amplitude of reflected phases, interference from scattered waves, and the need for advanced imaging techniques. To address these limitations, we apply 3D Reverse Time Migration (RTM) to reconstruct reflected wavefields and assess the feasibility of elastic Least-Squares Migration (LSM) to enhance resolution.

Preliminary results demonstrate that earthquake-generated reflections, when properly processed, yield images that serve as new constraints on mantle structure. We highlight examples where ERS has successfully retrieved reflectivity information and discuss its implications for mantle heterogeneities, subduction dynamics, and ultra-low velocity zones (ULVZs) at the CMB.

These findings suggest that ERS has the potential to bridge the gap between global seismology and higher-resolution imaging, offering a new perspective on deep Earth structures.

## S17 Decoding the Earth's interior through seismic anisotropy: Implications from modeling and observations

### AS25-0229

# Intrinsic Flow Mechanism in the Inner Core Driven by Anisotropic Thermal Conductivity of Iron: Influence of Stratification and Heterogeneity Length-scales

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Seismic observations indicate that Earth's inner core (IC) exhibits cylindrical anisotropy, with the fast axis aligned to the rotation axis, magnitude increasing radially inward, and displaying a hemispherical dichotomy. While several mechanisms have been proposed to explain this anisotropy, none fully account for its orientation and spatial patterns. The prevailing hypothesis suggests that anisotropy arises from the alignment of intrinsically anisotropic iron (Fe) crystals during core growth, but the underlying geodynamic processes remain uncertain.

We propose a new mechanism for texture development in the IC driven by the intrinsic anisotropy of Fe's thermal conductivity, which influences heat flow as the IC conductively cools [Das et al., 2025 (In review)]. This process generates anisotropy without requiring external forcing from the outer core or mantle, relying solely on intrinsic IC properties. A key motivation for this approach is its potential to explain hemispherical variations naturally, even if the IC undergoes slow rotation relative to the mantle.

Since hexagonal close-packed (hcp) Fe is both elastically and thermally anisotropic, its preferred orientation affects local heat flow, producing temperature anomalies that drive buoyancy-driven flow, which in turn reinforces texture development. We have tested this mechanism for a neutrally stratified IC using an initial texture with strongest alignment at the IC center that decreases radially outward. We aim to model the temporal evolution of texture and flow in a stratified IC and assess how small-scale anisotropic variations influence flow strength and stress that align the Fe crystals.

## AS25-0241

# Mantle flow and slab dynamics beneath Adria: new insights from SKS splitting with AdriaArray

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A key unresolved question in the central Mediterranean is whether a slab window exists beneath the Dinarides and how it influences mantle flow. Seismic anisotropy from SKS splitting provides crucial constraints on upper mantle deformation, but previous measurements in this region have been sparse. Using data from the newly deployed AdriaArray and permanent stations, we analyze SKS splitting with eigenvalue and transverse energy minimization methods to ensure robust, consistent results. SKS windows are automatically selected based on signal-to-noise ratios and dominant wave periods. To correct for misalignment, we use Rayleigh-wave polarization and subsequently verify the correction by comparing SKS source polarization with theoretical backazimuths. Our results reveal striking lateral variations in mantle flow. Across the Dinarides, slow seismic velocities coincide with a possible slab window, where SKS fast polarization transitions from being perpendicular to the orogenic trend to a NW-SE orientation beneath the Pannonian Basin. Further south, at the Dinarides-Hellenides transition, the Adria slab emerges as a high-velocity anomaly, and SKS fast polarization vectors rotate around it, indicating toroidal flow. These findings provide new constraints on the interaction between subduction-driven flow and slab dynamics in the central Mediterranean.

## AS25-0275

# Comparative analysis of transform fault evolution from lithospheric seismic anisotropy along the San Andreas system

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Plate boundaries and with them the stressing of earthquake-generating faults evolve based on a complex interplay of frozen-in lithospheric structure and tectonically evolving crustal and lithospheric damage and fabrics, driven by convection. While there are a range of observations hinting at strain-dependent fault roughness and seismicity distributions responding to fault maturity, such observations remain to be integrated into a comprehensive quantitative framework. Here, we contribute new constraints on the deep component of such a damage model by focusing on the analysis of crustal anisotropy from receiver function measurements along the San Andreas transform fault system. We analyze existing permanent and temporary deployment seismological broadband data, including from our UTIG Mojave experiment. Our results provide new constraints on crustal fabrics for a range of faults within the system, spanning incipient, low offset, intermediate, and mature strands of the fault network. We place our findings into context by consideration of the distribution of seismicity, fault geometries, as well as other constraints on anisotropy of the crust and mantle. Our analysis shows a powerlaw type increase of deep crustal anisotropy with fault offset, and those anisotropic regions span depths below the brittle-ductile transition. We discuss the results in the context of our understanding of brittle fault and ductile shear zone evolution and strain localization.

## AS25-0290

# Inversion of antipodal PKPab waves by the adjoint method to reveal radially anisotropic Vp structure at the core mantle boundary

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We combine new observations of antipodal PKPab seismic waves with the adjoint method to perform an inversion of the radially anisotropic Vp structure at the base of the lower mantle. We have carefully examined antipodal stations with high S/N ratios for both the vertical and horizontal components over the past 30 years and selected 23 source–receiver pairs with epicentral distances greater than 178.0 degrees and Mw values less than 7.0. We calculate synthetic seismograms with an accuracy of 6.9 s and perform an inversion of the radially anisotropic Vp structure at the base of the lower mantle by the adjoint method. The results of our inversion show that vertically polarized Vp is dominant within the LLVPs of the Pacific and African regions. These features are characterized by relatively small spots of high vertically polarized Vp anomalies, which may be interpreted as the locations of ascending mantle plumes inside LLVPs in the Pacific region. Our results do not agree with previous observations, which show that plumes are found at the edges of LLVPs and suggest that the plumes originate from impingement by downgoing slabs at the base of the mantle. Instead, our results suggest that LLVPs are not thermally stable for hundreds of million years.

## AS25-0334

# How fabric transitions in the mantle play a role in the formation of anisotropy and the propagation of seismic waves

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Mantle fabric transitions have been proposed to explain a number of structures that remain enigmatic, yet not entirely inexplicable, such as (i) the attenuation of seismic anisotropy with depth in the upper mantle (UM), (ii) the ubiquitous anisotropy in the mantle transition zone (MTZ) around subduction zones, and (iii) the existence of regional discontinuities in the upper lower mantle (LM, 800–1300 km). Recently, the microscopic flow properties constrained from high-PT experiments of bridgmanite (i.e., the most abundant anisotropic constituent in the LM) exhibit a pressure-dependence similar to olivine; whereas that of wadsleyite (i.e., that in the MTZ) appear to be sensitive to temperature and water content. Using these experimental data, we predict the patterns of large-scale anisotropy in the mantle close to a subducting slab where vigorous straining Is anticipated by combining geodynamic, CPO, and elasticity modeling in one self-consistent forward approach. The anisotropy models show consistency with tomographic observations, implying that the variability of anisotropy may be due to fabric transitions resulting from changes in the deformation patterns. Finally, using 3D waveform modeling, we interrogate these anisotropy models to study the behavior of certain seismic phases such as the splitting of PS waves in the presence of UM anisotropy and the deflection of body wave precursors off the mid mantle due to changes in textural properties.

## AS25-0345

# The impact of source-side subduction on PKP differential times and measurements of inner core anisotropy

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There is observed to be directional variation in measured PKP differential times, indicating that Earth's inner core is anisotropic – constraining this anisotropy is key to understanding the history and evolution of the inner core. PKP phases, however, have also been shown to be strongly dependent on 3D structure in the mantle, and disentangling these signals is important if we are to better constrain inner core anisotropy. Many earthquakes used to study the inner core occur in subduction zones, which are associated with strongly positive velocity anomalies, but the effect of this on the measurements has not yet been investigated.

We have used AxiSEM3D to forward model the effect of a source-side slab on PKP differential times, finding that a slab can introduce artefacts of several seconds. We have subsequently examined a large data set of measurements on order to assess if source-side subduction has a detectable influence on the data. We have also assessed the effect of the Scotia slab specifically to see if this contributes to observed anomalous measurements originating from the South Sandwich Islands. We find that the signal of source-side subduction in the data is weak, and that the magnitude of anisotropy required by the data is not affected by source-side subduction. Furthermore, the Scotia slab is very unlikely to be the cause of the anomalous measurements from the South Sandwich Islands.

## AS25-0427

# Anisotropic tomography and mantle dynamics of the North China Craton

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High-resolution 3-D images of isotropic P wave velocity (Vp), azimuthal anisotropy (AAN), and radial anisotropy (RAN) down to 700 km depth beneath the North China Craton (NCC) were obtained by inverting a great number of high-quality arrival time data recorded at 1,374 portable seismic stations and 635 permanent stations in the study region. The results reveal new and detailed features of the upper mantle structure beneath the NCC. The fast velocity directions (FVDs) of azimuthal anisotropy are mainly NW-SE under the Alaxa block, and NE-SW beneath the Tibetan Plateau. Low-Vp anomalies with positive RANs (i.e. horizontal Vp > vertical Vp) are revealed at 100–200 km depths under the Tibetan Plateau, reflecting frozen-in anisotropy in the thick lithosphere. In Datong volcano area, negative RAN occurs right below the volcano, suggesting that the Datong volcano is fed by hot upwelling flow from the lower mantle associated with collapsing of subducted slab materials down to the lower mantle. Connected with a large low-Vp anomaly beneath the eastern NCC above ~250 km depth, it is suggested that the hot upwelling flow under Datong may migrate laterally to the asthenosphere under the eastern NCC and contribute to the lithospheric delamination and destruction there.

## AS25-0570

# Influence of plate motion and collisional tectonics on active deformation beneath the Bhutan Himalaya

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Seismic anisotropy enhances our knowledge of the deep structure of the Earth and the causative mechanisms of deformation beneath a particular tectonic region. The primary objective of this research is to study the anisotropic behavior, deformation patterns, and complex geodynamics beneath the Bhutan Himalaya. We have used the Shear wave splitting (SWS) analysis of core refracted phases (SKS, SKKS, and PKS) to obtain anisotropic parameters such as first polarization direction (Φ) and delay time (δt) at the location of 52 broadband seismic stations. Our results show a strong coherency with the alignment of major geological or tectonic structures in close vicinity, whereas the majority of measurements represent the current deformation pattern of the mantle under this particular tectonic setting. We have observed multifaceted anisotropy directions of SWS observations; ENE-WSW to E-W in the southern region of Bhutan, ~NE-SW in the central region, and ~ N-S trend of FPDs in the northern region, suggestive of complex geodynamics scenario beneath this Himalayan region. The majority of splitting measurements represent the delay times between 0.70 s to 1.50 s, suggesting the significant anisotropic nature of the lithosphere beneath Bhutan. The disparate behavior of deformation patterns beneath Bhutan is suggestive of the influences from the collisional tectonics in the southern part, whereas the Absolute Plate Motion (APM) of the Indian plate due to the basal drag at the base of the lithosphere is controlling the deformation at the central and majority of parts of Bhutan.

## AS25-0607

# A probabilistic approach to seismically imaging Earth's anisotropic interior with applications to subduction zones and volcanic systems

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Seismic anisotropy—the directional dependence of seismic wave speeds—provides a unique view into the past and present deformation of Earth's interior. However, constraining Earth's anisotropic heterogeneity remains a challenge primarily due to imperfect data coverage combined with the increased number of free parameters required to describe elastic anisotropy. And yet, exploring this more complex model space is critical for the interpretation of seismic velocity anomalies which may be significantly distorted if anisotropy is neglected. In this presentation, I will discuss the application of transdimensional Bayesian inference for constraining 3D anisotropic structures in relation to subduction zone dynamics and volcanic processes. Key developments include moving beyond simplified assumptions regarding the orientation of anisotropic fabrics (i.e. from azimuthal and radial parameterisations to tilted-transversely isotropic models), the integration of multiple and complementary seismic observables (P and S body wave arrivals, shear wave splitting measurements, and surface wave constraints), and the exploration of model uncertainty and parameter trade-offs. I will discuss how applying these imaging approaches to subduction systems in the Western USA yields new insights into the geometry of mantle flow, the nature of seismic velocity heterogeneity, and trade-offs between isotropic and anisotropic features. At smaller scales, I will highlight how new anisotropic tomography reveals the structure of the magmatic plumbing system beneath Mt. Etna (Italy) and provides constraints on the geologic processes controlling crustal stresses.

## AS25-0758

# Towards constraining global-scale lowermost-mantle anisotropy using normal modes

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The relation between seismic anisotropy and flow-induced deformation in the mantle has the potential to constrain large-scale patterns of mantle dynamics. Global-scale, 3-D mantle models of radial anisotropy have mostly been inferred from shear-wave splitting and surface-wave phase velocities, and agreement between models in the lowermost mantle is poor. Global-scale mantle models of azimuthal anisotropy are limited to the upper mantle and the transition zone. Here we assess the ability of a different type of seismic data, normal modes, to constrain global-scale radial and azimuthal anisotropy, focusing on the lowermost mantle. Normal modes are whole Earth oscillations that are induced by large earthquakes and have sensitivity to large-scale elastic structure throughout the entire Earth. Normal-mode splitting functions have previously been used to infer azimuthal anisotropy in the upper mantle and the transition zone, but the large number of model parameters for a fully anisotropic medium limits their resolvability. We perform a principal component analysis on the sensitivity kernels of the normal-mode dataset, allowing us to determine which elastic parameters will account for most of the data variations. We find that the principal component analysis successfully reduces the number of model parameters and that there is significant sensitivity to radial and azimuthal anisotropy throughout the entire mantle, allowing for a future inversion of normal-mode splitting functions for global-scale mantle anisotropy.

## AS25-0810

# Understanding seismic anisotropy observations in the context of 3D slab-induced flow in the Cascadia subduction zone

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Characterizing the structure of the subducting slab in the Cascadia subduction zone (CSZ) is a crucial step in predicting and preparing for an inevitable megathrust event. The CSZ has a low rate of background seismicity relative to other subduction zones, which makes it difficult to construct seismic tomographic imagery of the slab geometry. Mantle flow patterns around the slab and stress transmitted to the shallow megathrust are governed by the 3D slab geometry. However, existing studies disagree on many aspects of Cascadia slab geometry, including the presence of a large gap in the Gorda segment beneath Oregon, the slab's depth extent, and the northern boundary of the CSZ. Although mantle flow patterns around the Cascadia slab are poorly constrained, seismic anisotropy observations obtained from shear wave splitting (SWS) measurements can be related to flow patterns in the upper mantle around the slab through geodynamic models. Here we aim to compare predicted anisotropy and tomography from existing 3D geodynamic models of various slab geometries with SWS observations and seismic tomography models of Cascadia. Our approach will leverage the ECOMAN software, which uses D-REX to calculate lattice-preferred orientation due to shear deformation, FSTRACK to predict seismic anisotropy, and PSI_D to predict seismic tomography. We anticipate that our results will help refine future slab models by providing a new constraint on slab geometry and flow in Cascadia. On a global scale, our proposed methods could improve understanding of mantle flow and upper mantle structure in regions with complex flow and significant subduction-related hazards.

## AS25-0945

# Effects of crystal-fabrics and mineral modes on seismic anisotropy in the lithospheric mantle: a numerical analysis using Horoman peridotites, Japan

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We conducted a numerical analysis on the seismic velocities in mantle peridotite using the elastic constants and crystallographic preferred orientations (CPOs) of its primary minerals: olivine, orthopyroxene, and clinopyroxene. This study involved three peridotites to investigate the differences in CPOs within the lithospheric mantle. The analysis included olivine proportions ranging from 50% to 100% mechanically, while the proportions of the two pyroxenes varied from 0% to 50%.

As the proportion of pyroxenes increased, there was a reduction in the maximum P-wave velocities (8.35–9.14 km/s) and P-wave anisotropies (5.51–14.50%) across all samples. Nevertheless, the S-wave velocity remained largely unchanged. Additionally, we utilized a Vp-Flinn diagram (Michibayashi et al., 2016) to investigate the interactions among the three minerals and assess the impact of CPOs. This analysis indicates that the olivine CPO in peridotite predominantly influences the propagation patterns of P-wave velocities.

Consequently, the non-negligible effects of mineral modes and CPOs led to differences in seismic velocities, indicating that the presence of orthopyroxene/clinopyroxene and olivine CPOs might be crucial for assessing seismic anisotropy in the upper mantle. The variations in mineral modes and CPOs in Horoman peridotites could be attributed to melt segregation (Takahashi, 1992) and multiple deformation processes (Matsuyama & Michibayashi, 2024), respectively. Therefore, these geological factors could potentially affect the in situ seismic anisotropy within the upper mantle.

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## AS25-1033

# Quality Control of 40 Years of Seismic Data in Australia and Its Impact on Seismic Structure and Anisotropy Measurements

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Seismic imaging techniques are essential for investigating Earth's structure, providing insights into geological and geodynamic processes. The accuracy of these methods relies on proper seismic instrument deployment, sensor performance, and long-term data maintenance. To ensure reliable results, rigorous quality assurance and quality control (QA/QC) procedures are necessary, including instrument orientation correction, GPS clock drift adjustments, and metadata verification.

In this study, we conduct an extensive QA/QC assessment of passive seismic data collected over the past 40 years from temporary deployments in Australia (https://auspass.edu.au/), the Australian National Seismograph Network (ANSN), and the AusArray network (https://www.eftf.ga.gov.au/ausarray). AusArray, initially funded through the Exploring for the Future program continues with an expanded deployment as part of the Resourcing Australia's Prosperity initiative. We demonstrate how QA/QC improvements enhance the accuracy of noise correlation functions in ambient noise tomography and how instrument orientation corrections refine anisotropy measurements from shear-wave (SKS) splitting. Additionally, we assess the impact of data quality on detecting seismic discontinuities, including the Moho, lithospheric boundaries, and mantle transition zone discontinuities (410 km and 660 km).

Our preliminary results show how improved data integrity leads to better constraints on seismic velocity variations and anisotropy across Australia, revealing key features of the lithosphere and upper mantle. By systematically addressing quality control issues, this study underscores the critical role of QA/QC in refining seismic models and advancing our understanding of the Australian continent's deep structure.

## AS25-1158

# S-wave anisotropy patterns of three scales in the SE margin of Tibetan plateau

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It is well known there are strong tectonic movement and high seismicity in SE margin of Tibetan Plateau, due to the collision among the Indian plate and the Eurasian plate and the South China block. This study reveals the seismic anisotropy of S-waves in the scales of the upper crust, the whole crust and the lithosphere in the study area.

The S-wave splitting from the local earthquake records indicates seismic anisotropy in the upper crust. The polarizations of fast S-waves (PFS) show the dominant orientation generally in NS, but in NNW, NNE or other orientations in different subzones, sometimes in scattering in local area. The PFS is generally consistent with the principal compressive stress or the local tectonic lines such as faults.

The azimuthal seismic anisotropy in the whole crust is obtained by the receiver function data. The pattern of the fast orientations generally shows harmony with the PFS, although different in some area. However, the fast orientations are scattered somewhere. It is important to analyze influences from the layered structure, data quality or calculation error.

The lithospheric anisotropy, also including the topmost asthenosphere, is obtained in the fast orientations of XKS (i.e. phases SKS, PKS and SKKS) splitting. It is clearly characterized by the subzones the north and the south, cut by about 26°20′N (Gao et al. 2020), the fast direction in NS in the north and in EW in the south respectively.

Seismic anisotropic patterns in multi-scales suggest more information on deep tectonics and migration process [supported by NSFC Project 42330311].

## AS25-1309

# Explore the relationship between crustal low-velocity zones and seismogenic tectonic environment in the northeastern Tibetan Plateau

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The growing marginal region of NE Tibet is considered the current expansion frontier, where several strong earthquakes (~ M7) happened since 1990, forming a T-shaped belt by linking with the Qilian-Haiyuan fault, an important active strike-slip fault zone in NE Tibet. The low-velocity zones represent weak sections of the seismogenic crust, which may be due to a fluid-filled, fractured and over-pressurized rock matrix that contributed to the initiation of the large earthquake. However, the image resolution and accuracy of low-velocity zones under a T-shaped belt remain insufficient due to the small size and the deformation is difficult to constrain directly.

We preferred to conduct anisotropic inversion of NE Tibet by using the travel time of P-wave other than S-wave for higher picking accuracy and applied a recently developed crustal three-dimensional P-wave seismic anisotropy joint tomography. By using Pg and Pn travel times of local earthquakes recorded by regional permanent seismic stations, especially with additional Pivotal PmP data, we can improve the resolution of the deep crust. Our anisotropic images suggest that the low-velocity zones in the middle to lower crust lead to the intracrust and crust-mantle decoupling in the transition zone of NE Tibet, rather than deformation coherently from the crust to the asthenosphere by shear-wave splitting studies. Preliminary analysis of the sequence of strong earthquakes and deep deformation characteristics of the Qilian-Haiyuan fault zone helps to enhance the knowledge and understanding of the role of the deep-crustal low-velocity zones in the seismogenic mechanism of strong earthquakes.

## S18 Earthquake Source Mechanics

### AS25-0015

# Spatio-temporal scaling relationship between earthquake and oceanic phenomena

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Owing to dense network of seismological and geodetic observations, various types of slow earthquake phenomena has been detected not only in the deeper extension of seismogenic zone but also in the shallower extension. Around the major subduction troughs such as Hikurangi, Nankai Trough and Japan Trench, ocean current meander generates meso-scale eddies, which causes ocean impact on the seafloor pressure. In recent studies, we have investigated the spatio-temporal scaling relationship of the impact on the seafloor pressure between earthquake and oceanic phenomena. The conclusion is summarized as (i) the spatio-temporal scaling of the meso-scale eddy is similar to slow slip event and afterslip, (ii) these slow earthquake phenomena could be affected by the ocean impact caused by the meso-scale eddy in the duration and termination processes. In this presentation, we introduce some examples of observed slow slip events.

## AS25-0048

# Narrow intermediate-depth seismogenic band related to flexural strain in relatively dry Peruvian flat slab

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The distribution and rupture properties of intermediate-depth earthquakes (70–300 km) provide insights into the interior stress state of the subducting plate, its petrological composition, and the subduction history. Here we evaluate the kinematic spatio-temporal rupture evolutions of four M7+ intermediate-depth earthquakes beneath Peru between 1997 and 2021 using teleseismic waveforms, which reveal similar rupture behavior over a limited depth range within the flat-slab segment. The intermediate-depth seismogenic zone is confined within a narrow band ~20 km thick near the slab surface, as also found in Pampean and Mexican flat slabs, contrasting to the broader seismicity distributions in the adjacent normally-dipping segments. The elongated earthquake ruptures in flat slabs with few aftershocks and the narrow, sparse seismicity bands are attributed to flexure from along-dip slab steepening and limited dehydration reactions within relatively dry flat-slab segments. Conversely, the diffuse seismicity in adjacent normally-dipping segments is likely associated with more widespread dehydration reactions.

## AS25-0067

# How Mantle-Wedge Serpentinite Controls Fast and Slow Earthquakes in Warm and Cold Megathrusts

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By synthesizing earthquake studies, heat flow observations, thermal modelling, and laboratory rock friction findings, I postulate how mantle-wedge serpentinite may control megathrust seismogenesis at and downdip of the mantle wedge corner (MWC). Along lukewarm to very cold megathrusts such as in North-central Chile and Northeast Japan, the serpentinite at the MWC is rich in lizardite, giving rise to a “soft barrier” that impedes but cannot always stop seismic slip. Farther downdip, the serpentinite is rich in antigorite which facilitates seismic slip. In these subduction zones, many moderate-size megathrust ruptures are confined to be mostly updip or down-dip of the MWC barrier, but very large ruptures overcome the barrier (e.g., 2010 M=8.8 Maule and 2011 M=9 Tohoku). In the deepest part of the large ruptures, fault gouge becomes sluggish due to high temperature, but embedded small high-concentration antigorite patches can undergo fast slip with high stress drop. This explains why this zone exhibits small coseismic slip but strong radiation of short-period seismic energy. In contrast, very warm megathrusts such as in Nankai and Cascadia do not have a lizardite barrier, but the seismogenic zone is terminated at depths shallower than the MWC by thermally activated creep. Importantly, shallow metamorphic dehydration of the young and warm slab causes antigorite saturation in the tip area of the mantle wedge. The resultant near-lithostatic fluid pressure facilitates episodic slow slip instead of earthquake rupture. Under this fluid pressure condition, the high-concentration antigorite patches become sources of seismic tremor and LFE accompanying the slow slip.

## AS25-0091

# Predictable and Unpredictable Aspects of Earthquakes from P-wave Onsets: Vigorous Ruptures Finish Quickly

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This study explores whether there are any predictable aspects of the rupture process from the initial P-wave. We propose that the moment-normalized duration of an earthquake negatively correlates with its initial stress drop, which is measured from the slope of the acceleration record shortly after onset. Since 2007, this slope, B, has been used in the Japanese earthquake early warning system as an indicator of epicentral distance, yet it also provides deeper insights into earthquake dynamics and wave propagation. Utilizing high-sensitivity seismograms from approximately 800 Hi-net stations and combining manually picked P-wave arrival times and focal mechanisms for about 1800 earthquakes, we estimate B for each station and earthquake pair within a 0.1 s window. We confirm that B decreases from the square to the fourth power of the P-wave travel time. Residuals between observed values and travel time dependencies are further decomposed into event and site terms, alongside radiation pattern dependency, which is close to a power of 0.5—possibly reflecting complex rupture processes that begin at a minute scale. The event term primarily represents the initial stress drop, showing minimal dependency on final size and a clear dependency on event depth, mirroring observations of average stress drop. This term also shows a statistically significant correlation with the moment-normalized duration estimated independently using S-waves, suggesting limited predictability of the rupture process. The site terms, which correlate with tectonic structure, help reduce errors in estimating arrival times, especially for nearby earthquakes, thus offering practical benefits for early warning systems.

## AS25-0112

# Rupture phases reveal geometry-related rupture propagation in the 2023 Mw 7.8 Kahramanmaraş, Türkiye earthquake

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Understanding and deciphering wiggles from seismograms has been a long endeavor to understand the internal structure of the Earth and to explore earthquake source properties. However, coherent phases directly associated with rupture propagation have not been observed during natural earthquakes. Here we decipher the continuously distributed strong motion data along the East Anatolian Fault to track the rupture in the 2023 Mw 7.8 Kahramanmaraş, Türkiye earthquake.

To understand the observed complex near-fault velocity pulses, we combine the dynamic rupture simulation and data analysis to identify the velocity pulses associated with the rupture front. The model results show dependence of the timing and shape of velocity pulses on the distance to the fault. In addition, we observe atypical negative fault-parallel velocity pulses and multiple fault-normal pulses on some stations near fault bends. Through multi-segment model analysis and dynamic rupture simulations, we prove that these atypical pulses are caused by rupture deceleration at fault bends. Based on the above analysis, we then identify the velocity pulses associated with the rupture front at all stations as rupture phases, which reveal a subshear-supershear-subshear transition along the Amanos segment. The supershear propagation is suggested to appear on a segment with relatively flat fault trace and end at a fault bend. Our study highlights the complexity and superior application of near-fault data in studying earthquake source dynamics.

## AS25-0113

# Inferring Rupture Directivity Using Single Near-Source Record for the 2024 M4.7 Feidong Earthquake, Anhui Province, China

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Determining the rupture directivity for small earthquakes is challenging due to the small source dimension and limited resolution of far-field observations. Current studies on the rupture propagation of small earthquakes are mostly based on seismic networks, as the asymmetric ruptures can cause azimuth-dependent observations. In recent years, the burst of near-source observations provides great opportunities to study earthquake rupture.

Here we present the rapid determination of the rupture directivity for the 2024 Feidong M4.7 earthquake using only one strong motion station located 4 km from the epicenter. We find that the polarization of S waves evolves during the rupture, indicating an azimuth change during the rupture propagation. Through comparing the data with the synthetic waveforms, we infer that the M4.7 event propagated dominantly to the southwest on the dextral Tanlu fault. Our inference is further validated through comparing the data with records at local stations for M3 earthquakes in the Feidong sequence. Our study highlights the superior application of near-source observations in earthquake source studies

## AS25-0160

# Global distribution of anti-repeaters

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Anti-repeating earthquakes have been recently introduced as earthquake pairs with similar locations and opposite fault mechanism. So far, only a few cases of anti-repeaters have been observed, being detected based on the anti-correlation of their seismic waveforms. The conditions for the occurrence of anti-repeating earthquakes, requiring strong spatial and/or temporal stress anomalies, may seem peculiar. However, the fact that the few available observations sample different seismological environments, including tectonic, volcanic and induced seismicity, suggest that anti-repeaters might be more abundant than we think. Here, we report the results of a global investigation, where we processed 48 years of earth seismicity, scanning the Global CMT moment tensor catalog in search of pairs of earthquakes with similar centroid locations and opposite moment tensors. We present here a first, global catalog of anti-repeaters. We could identify thousands of anti-repeaters, clustering at hundreds of locations on earth, occurring at different depths, in different tectonic settings, as well as in volcanic environments, and with a broad range of magnitudes and moment tensor configurations.

## AS25-0196

# Multi-frequency fault Rupture process of the 2016 Kumamoto earthquake: Insights from Multi-Beam Back-Projection and Strong Motion Records

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I investigated the broadband frequency fault rupture process of the April 16, 2016, Kumamoto earthquake (M7.1) using the multi-beam seismic back-projection method in combination with a dense array of near-source strong motion records (K-NET/KiK-net networks). This study examines the spatio-temporal characteristics of multi-frequency radiation, its relationship with the off-fault rupture process, and the rupture termination process within the Aso caldera.

To achieve this, I computed the spatio-temporal evolution of maximum grid energies across four frequency bands (0.1–0.5, 0.5–1, 1–5, and 5–10 Hz) within a 3D grid mesh covering the region from the Hinagu fault to the Aso caldera. My results indicate that the rupture lasted 22 seconds, propagating 45 km northeastward from the Hinagu fault region to the Aso caldera. High-frequency (HF) radiation (1–10 Hz) was strongly emitted between 3–10 s, primarily from the hanging wall wedge of the Hinagu fault, at depths ranging from 15 km to the surface. In addition, the distribution of HF radiation largely coincides with regions where JMA seismic intensities exceeded 6, suggesting that off-fault deformation played a crucial role in generating both high-frequency radiation and the observed strong ground motions.

Furthermore, two distinct episodes of low-frequency radiation were observed within the Aso caldera between 17 and 22 seconds. The first occurred beneath Nakadake volcano, likely within its shallow magma chamber, while the second was associated with the Miyaji faults to the northeast. These findings suggest that the rupture termination process of the earthquake was strongly influenced by the complex subsurface structures beneath the Aso caldera.

## AS25-0202

# A dense focal mechanisms catalogue for the Atacama segment in Chile (24◦S–31◦S) using deep learning polarity picking

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The Atacama segment in Northern Chile, a persistent seismic gap since 1922, is a highly active subduction zone. While a dense seismicity catalog (M>1.5) exists, focal mechanism solutions are sparse. Mapping the source mechanisms of small to moderate earthquakes would enhance the subduction interface structural image, inform the stress state of the subducting slab, and characterize episodes of transient slow slip. In addition, it could provide insight into processes in the mantle wedge and the upper plate.

Accurate P-wave polarity picking is crucial for determining focal mechanisms, yet difficult to automate. This challenge becomes even more pronounced for smaller magnitude events with their low signal-to-noise ratio. For automatic P-wave polarity picking, we employ a CNN-based model similar to the one proposed by Ross et al. (2018). While their model was only trained and evaluated in Southern California, in our application we are interested in the transferability to different regions and tectonic settings. We perform a systematic benchmark of in-domain and cross-domain performance over six hand-curated datasets. Transferability between regions is good, but cross-domain performance remains lower than in-domain results. As a solution to this degradation, we explored joint training on multiple datasets to improve generalization.

Based on systematic cross-testing of the polarity picking model on these benchmark datasets, we identify the best model and apply it to the unpicked Chilean earthquake catalogue to determine first-motion polarities. Based on these polarities and P/S amplitude ratios, we determine focal mechanisms using the SKHASH package.

## AS25-0211

# Characteristics of seismogenic faults at Koyna-Warna, western India from precise locations and source mechanism of reservoir triggered earthquakes

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The Koyna-Warna region situated in the Deccan Volcanic Province of western India is one of the popular sites of artificial water reservoir triggered seismicity (RTS). In this study, we investigate the seismic activity for the period from 2015 to 2024 based on recordings from the combined seismic network i.e. a borehole network of eight stations and a surface broad-band network of 23 stations operating in the study region which provided the best possible azimuthal coverage for the seismic zone. A unique set up of borehole stations have provided much constraint on achieving the improved absolute locations of earthquakes. We computed the relocations of earthquakes using the joint hypocentral determination and HypoDD techniques. The refined epicentres provide insights into the characteristics of the fault zones down to a resolution ranging typically as low as 200 m. The distribution of hypocenters suggests that the seismic zone is characterized by N-S, NNE-SSW and NW-SE oriented seismicity trends. Inverting for source mechanism of earthquakes of M~3 and above revealed faulting mechanisms are predominantly left-lateral strike-slip on NNE-SSW segment which is well correlated with the Donachiwada fault zone in the vicinity of the Koyna Dam, while normal faulting events typically occur on NW-SE and NS-trending seismicity clusters and are well correlated with the faults mapped by aeromagnetic and LiDAR studies in the vicinity of the Warna Reservoir. The spatial and depth-section of the seismicity patterns also provided insights on the characteristics of seismogenic faults of the Koyna-Warna region.

## AS25-0216

# Detecting Annual-Scale Interplate Coupling Variations by a Method Combining Intraplate Earthquakes and Geodetic Data: Case Studies from Tohoku-Oki and Nankai

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We propose a method to infer detailed spatiotemporal variations in interplate coupling by integrating geodetic and seismic data. The method evaluates whether focal mechanisms of intraplate earthquakes near the plate interface align with the stressing rate caused by a geodetically derived slip-deficit rate model, assessing deviations from a steady locked state. We define a long-term slip-deficit rate distribution as the reference plate coupling state and the associated stress changes as the reference stressing rate tensors. A misfit angle is introduced as the angle between an earthquake's slip direction and the tangential traction predicted by the reference stressing rate tensor. Smaller misfit angles indicate persistence of the reference plate coupling state, whereas deviations, such as those caused by large earthquakes or SSEs, result in larger misfit angles. Applied to the Tohoku-Oki plate boundary over a quarter-century, including the 2011 Mw9.0 earthquake, the method detects known phenomena, such as the decadal evolution of aseismic slip off central and southern Tohoku before the earthquake. It also reveals complex spatiotemporal behaviors, capturing changes in the locked state that geodetic data alone could not detect. Motivated by these results, we applied the method to the Nankai Trough and detected spatiotemporal variations associated with long-term slow slip events. The proposed method enables detection of annual-scale variations and finer-scale spatial changes in the locked state, providing a new tool for monitoring interplate coupling evolution and assessing seismic hazards.

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We used the F-net moment tensor catalog (NIED) and the GEONET F3 Solution (GSI).

## AS25-0242

# Fault Population Characteristics from Microseismicity and Fault Plane Solutions in the Gulf of Corinth

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The Gulf of Corinth, one of the most seismically active regions in Europe, provides a natural laboratory for studying the fault population characteristics and stress interactions. To address this task, we examine the properties of the major and subsidiary active faults using microseismicity and fault plane solutions, offering insights into fault geometry, stress distribution, and deformation processes.

By analyzing high-resolution seismic catalogs and focal mechanisms, we characterize fault orientations, slip tendencies, and kinematic behaviors. Clustering patterns of microseismicity are engaged to reveal the segmentation of active faults and potential connections between structures. Fault plane solutions will provide crucial information on the prevailing stress regime, indicating variations in fault slip modes across different segments of the rift.

Results highlight the complex interaction between normal faults, revealing variations in strain accommodation and the role of secondary structures in the overall deformation pattern. The analysis also sheds light on stress field heterogeneities and their influence on seismicity distribution. These findings contribute to a better understanding of fault system evolution in extensional tectonic settings and have implications for seismic hazard assessment in the region.

By integrating microseismicity and fault plane solution data, this study advances knowledge on fault population dynamics, offering a framework for assessing seismic hazard in active rift environments.

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## AS25-0263

# Systematic Seismic Rupture Responses to Background Loading: Insights from Repeating Earthquakes

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Earthquakes repeatedly generate seismic slips in the same area, yet their final sizes vary. To elucidate the meaning of this variability, we analyzed a prominent sequence of repeating earthquakes from Japan's latest catalog. Specifically, we selected a representative sequence from the Igarashi (2020) catalog, consisting of 53 events (2003–2023). Despite being a typical example, waveform analysis revealed magnitude variations from Mw 3.0 to 4.0. These events exhibited a hierarchical structure, incorporating smaller (Mw<2.5) repeating earthquakes.

We estimated the moment-rate functions of the target Mw 3–4 events using the waveforms of these smaller events as empirical Green functions. The results indicate that these earthquakes were not simple repetitions but followed a more generalized recurrence pattern. Ruptures consistently initiated in the same patch. Before the 2011 M9 Tohoku earthquake, only a single patch ruptured. However, after the earthquake, a second adjacent patch also began to rupture. Over time, the events transitioned back to single-patch ruptures in a remarkably systematic manner, with decreasing slip and Mw. To further examine the relationship between initial momentum and final magnitude, we compared the 53 events with 40 smaller ones (Mw 2.0–2.5) but found no clear correlation.

Our findings demonstrate that earthquake rupture patterns systematically respond to background loading rate changes. Following major seismic events, increased loading can lead to greater slip and enhanced rupture complexity. These systematic responses reflect in situ frictional characteristics and suggest potential for improving physical models of rupture evolution. Subtle variations in repeating earthquake sequences can help constrain the factors that control rupture processes.

## AS25-0264

# A joint spatio-temporal investigation of stress drops and b-value of major seismicity in Italy for submission

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Fault stability is controlled by the balance between the accumulation of stress and the ability of the nearby crustal volumes to allocate it through their elastic properties avoiding accelerating strain localization. Even though the state of stress on fault is not accessible, it is possible to investigate different geophysical features which may provide useful information about the mechanical conditions of fault systems during the seismic cycle. Here, we perform a joint analysis of the stress drops of earthquakes and the b-value of seismicity in Italy. While the first parameter is a measure of the change in fault stress before and after the event, reflecting both mechanical conditions and frictional strength within the Earth's crust, the b-value is well-known to be somehow related to both fault roughness and accumulated stress. We examine major Italian seismic sequences from the last three decades, including the Colfiorito (1997–1998), Molise (2002), L'Aquila (2009), Pollino (2012), Sannio-Matese (2013–2014), and Amatrice-Visso-Norcia (2016–2017) events. Synchronous variations in b-values, calculated using different methods, and stress drops are consistently observed in both declustered and complete seismic activity.

Our findings suggest that a combined analysis of stress drops and b-values can enhance the understanding of physical processes in the brittle crust during seismic sequences. This multiparametric approach provides a more comprehensive view of fault behavior and stress dynamics, contributing to improved seismic hazard assessment.

## AS25-0291

# Complexity of source time functions of moderate crustal earthquakes in Japan

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The source time functions (STFs) of earthquakes vary from simple single peaks to complex multiple peaks. Previous studies based on global earthquake catalogs suggest that STF complexity is related to source location and/or fault mechanisms (Ye et al. 2018; Yin et al. 2021; Li 2022). In this study, STFs of ~1500 Japanese earthquakes are grouped by complexity, focusing on the numbe of peak, to explore their relationship with source characteristics.

The dataset consists mainly of shallow crustal earthquakes (M3–5). Their STFs were modeled by the combination of multiple point sources (Kikuchi & Kanamori 1982, 1986, 1991) from the apparent STFs at each observation station estimated by empirical Green's functions (Yoshida & Kanamori 2023). The STFs were grouped by a graph-based nonlinear dimensionality reduction of UMAP (Mclnnes et al. 2020) and a hierarchical clustering on the low-dimensional embedding map.

As a result, we obtained earthquake clusters with similar STFs. Almost half of the events belong to groups with simple STFs consisting of a single peak, and the other half belong to groups with complex STFs with multiple peaks. We found that the STF complexity showed no clear correlation with magnitude, source location, or fault mechanism. This suggests that the rupture process of crustal earthquakes occurring within the island arc of Japan can take a variety of styles, regardless of the region. The earthquakes with multi-peak STFs had higher radiated energy enhancement factor (REEF; Ye et al., 2018).

## AS25-0302

# Temporal and spatial characteristics of source parameters of earthquakes in Changning-Xingwen area

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An earthquake of $M_S$6.0 struck Changning Country in Sichuan Province on 17 June, 2019. It occurred at the southeastern margin of Sichuan Basin. Four aftershocks with magnitude larger than $M_S$5.0 occurred during the following days till to July 4, 2019. Based on the seismic phase observation report provided by China Earthquake Networks Center, we used double difference method to relocate earthquakes occurred during 2017 to 2019, and obtained 12 225 $M_L \geq 1.0$ events. The earthquake relocation results show than the events are concentrated in Changning-Gongxian and Junlian-Gongxian regions. In Changning-Gongxian region, the distribution of earthquakes presents NE direction with approximate 50 km and NW direction with approximate 10 km, respectively. In Junlian-Gongxian region, the distribution of earthquakes presents uneven intensity, the seismicity in east is dense while in west is sparse. In eastern segment of this region, the earthquakes present NE and SE directions. Meanwhile, the focal depth of relocated earthquakes ranges from 0 km – 15 km, and the mainly concentrated from 2 km – 8 km. Meanwhile, we calculated source parameters such as seismic moment, apparent stress, and stress drop based on waveforms of $M_S \geq 3.0$ earthquakes from January, 2017 to December, 2019. The results show that the apparent stress of $M_S$3.0–3.4 earthquakes significantly increased in Changning-Xingwen area before the moderate strong earthquakes, and most of the earthquakes above $M_S$4.0 occurred in the high apparent stress area of $M_S$3.0–3.4 earthquakes in the study area.

## AS25-0305

# Geodetically estimated interseismic asperities below oceanic basins bordered with slow earthquakes

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Locked asperities of plate boundary faults resist slipping until earthquakes are incurred. Therefore, slip deficit, also called coupling, is an interseismic proxy of seismic potential. However, when a part of a frictional interface sticks together (locked), its sliding surroundings are braked and slowed (coupled), so the coupled zone is an overestimate of the locked zone, which overlooks a gap of closely spaced asperities, underestimating their stress loading. Therefore, we have developed a method to estimate the locked asperities based on a physics-based model (Sato, Hori, & Fukahata, under review; arXiv:2409.14266); assembling various laws of friction and focusing on interseismic phases, we have found that locking (pre-yield) robustly means a stationary phase of zero slip rate while unlocking (post-yield) is also robustly synonymous with a quasi-static phase of zero stressing rate. By simulating this universal mechanics of locking and unlocking, we can simply estimate the locked asperities from geodetic data. Our study area is the Nankai subduction zone in southwestern Japan. Our inversion analysis of onshore Global Navigation Satellite System (GNSS) and offshore GNSS-acoustic data by Yokota et al. (2016) has detected five primary asperities correlated with five basins: Hyuga, Tosa, Muroto, Kumano, and Enshu, the envisioned rupture segments of the Mw 9.1 Nankai megathrust earthquake. We have also detected a locking gap separating western and eastern locking segments east of the Cape Shionomisaki, the stress loading concentration around which is highly consistent with slow earthquake activities and rupture initiation points of the 1944 Tonankai and the 1946 Nankai earthquakes.

## AS25-0369

# Earthquake Triggering Power Extends Below Instrumental Detection Limits

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Each earthquake redistributes stress within the crust, triggering cascades of aftershocks that theoretically extend to infinitesimally small magnitudes. This unconstrained proliferation poses the ultraviolet (UV)-divergence problem—where infinite small-energy events render models mathematically unstable and physically inconsistent—if a trunction is not introduced in the form of a lower triggering magnitude threshold ($m_0$). Current empirical studies have yet to conclusively determine whether $m_0$ exists or define its value. To address this gap, we introduce a novel ETAS model which replaces the conventional sharp magnitude cutoff for triggering magnitudes with a smooth transition function. It reflects the expected gradual decline in the aftershock-triggering capacity of smaller-magnitude earthquakes, offering a more realistic physical framework than abrupt thresholds. We found that comprehensive calibrations across long-term regional datasets (e.g., Italy, California, China) and AI-enhanced high-resolution catalogs reveal no evidence of $m_0$ above the smallest detected magnitudes. If $m_0$ exists, it likely lies below the completeness magnitude ($m_c$) of instrumental catalogs, approaching $m_c$ only in machine-learning-optimized datasets. Moreover, the absence of an observable $m_0$ suggests that most earthquakes be triggered from undetectably small earthquakes. Critically, even minor seismic events ($m_0<m<m_c$) could nucleate aftershock cascades that culminate in larger mainshocks, challenging conventional hazard models reliant on sharp triggering thresholds. These results underscore a fundamental limitation in observational seismology: the triggering dynamics governing detectable earthquakes are partially driven by processes below instrumental resolution. Consequently, hazard assessments should account for the latent contribution of sub-threshold seismicity to seismic risk, necessitating probabilistic models that integrate indirect evidence of microseismic activity.

## AS25-0420

# Seismic Source Characterization in Anisotropic Media: Impact of Lithospheric Anisotropy on Moment Tensors

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Kawakatsu (2024, BSSA) recently demonstrated that the systematic source-type dependence of the non-double couple (NDC) components of the GCMT moment tensors for shallow sources can be attributed to the presence of transverse isotropy with a vertical symmetry axis in the lithosphere, where the anisotropy parameter $\xi>1$. It is important to recognize that this is an intrinsic property of the moment tensor in an anisotropic medium as long as we remain within the Burridge-Knopoff-type framework and not merely an effect of unmodeled path influences. Given that most published moment tensor solutions adopt this framework, direct interpretations of MT solutions (such as slip directions) based on the assumption of an isotropic source region structure might be biased. To assess the significance of this effect, it is essential to investigate how realistic anisotropic structures may give rise to NDC components in moment tensors.

In this study, we aim to quantify this effect using surface wave anisotropy tomography models of the lithosphere. Our approach incorporates both radial and azimuthal anisotropy in the modeling of moment tensors, including NDC components, while assuming seismic sources as planar faulting. Preliminary global modeling suggests that azimuthal anisotropy may enhance NDC modeling; however, the extent of this improvement remains uncertain and is highly dependent on the assumed fabric structure. In contrast, regional modeling for areas exhibiting strong lithospheric anisotropy in tomography (e.g., Tibet) or unique tectonic settings, such as the outer rise regions of the Alaska-Aleutian and Kuril subduction zones, the significant impact of azimuthal anisotropy is clearly evident.

## AS25-0441

# Source process estimation with ocean bottom seismometer data for Mw-5 class moderate earthquakes

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Source process is useful information to understand the earthquake source physics. Usually, the source process can be estimated by the linear waveform inversion so that the observed data is reproduced by convolving the source time function and Green's function at each point on the source fault (Olson and Apsel, 1982; Hartzell and Heaton, 1983). Although a fine station coverage is preferable to constrain the rupture propagation direction, the onshore seismographs usually existed with a biased distribution from the earthquakes that occurred in an offshore region. One possible solution to use more stations with better coverage for such a situation is utilizing the ocean bottom seismometer (OBS) data.

In this study, we applied the waveform inversion proposed by Shibata and Aso (2025) to both onshore and offshore seismometer data. This method is a kind of the empirical Green's function (EGF) approach (Hartzell, 1978), utilizing waveforms generated from a nearby source with a similar focal mechanism. Shibata and Aso (2025) added radiation correction to the conventional EGF approach, which is advantageous for estimating source processes of $M_w$-5 class moderate earthquakes and utilizing OBS data. We exemplified the source process estimation for moderate offshore earthquakes in Japan with the Hi-net onshore and S-net offshore seismometer data (Aoi et al., 2020). As a result, the observed waveforms were reproduced well with a frequency of 0.2–2.0 Hz for both data. The moderate-scale source processes showed a complex rupture propagation as observed during large earthquakes.

## AS25-0446

# The source parameters and seismogenic environment of 2023 M6.2 Jishishan, Gansu earthquake sequence

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The M6.2 earthquake in Jishishan, Gansu Province, on December 18, 2023, caused extraordinary earthquake disasters. It was located in the northern part of the north−south seismic zone, which is a key area for earthquake monitoring in China. We used the newly built strong motion and traditional broadband seismic networks to obtain earthquake relocation, focal mechanism and rupture process of the mainshock. The relocation results indicated that the majority of aftershocks occurred at a depth of 12 km. The centroid depth of the main shock is similar with the depth of the maximum rupture of the mainshock. The focal mechanisms of the main shock and aftershocks are relatively consistent, and the P-axis orientation is consistent with the regional strain direction. There is a seismic blank area of M3.0+, about 3−5 km to the north of the main shock. It is suggested that the energy released by the main shock rupture is concentrated in this area. We inferred that the main shock was triggered by the main fault at the northern margin of the Lajishan Fault and that the movement of the main fault also activated some secondary faults. The compressive forces on both sides of the Lajishan Fault Zone led to the uplift of mountain areas, accompanied by some landslides, leading to this catastrophic earthquake event.

## AS25-0453

# Estimating moment magnitudes of moderate to large earthquakes in western China based on regional seismic records

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Timely and accurate estimation of earthquake moment magnitude is crucial for damage prediction and emergency response. However, determining a reliable value within ~10 minutes after origin time remains challenging. We present a novel and robust algorithm for estimating of moderate to large earthquakes using regional to teleseismic distance records. We tested the method on 22 earthquakes with Mw≥6.5 and shallow depths (western China, 2008–2023). The results demonstrate that the algorithm is stable and reliable, with estimates closely aligned with conventional solutions published by the USGS, showing a standard deviation of ~0.1. These estimates can be achieved within ~6–11 minutes of origin time. The algorithm effectively minimizes the impact of reflected phases in regional data and uneven station distribution, enabling rapid and accurate magnitude estimation for moderate to large earthquakes. The application of this method facilitates cross-validation with multiple magnitude scales, significantly enhancing both the speed and precision of earthquake response.

## AS25-0464

# Using k0 computed from ambient noise to improve source parameters estimation for microearthquakes recorded in High Agri Valley (southern Italy)

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In this study, we estimated $k_0$ values from both ambient seismic noise and local earthquake coda at eight broadband stations of the High Agri Valley Geophysical Observatory (HAVO). We estimated the $k_0$ parameter at each station using ambient seismic noise in the frequency range of 15–40 Hz. Our results show that $k_0$ varies between 0.03 s and 0.04 s for most of the stations and is well constrained in the selected frequency range. We used the estimated $k_0$ values to correct for near-site attenuation the high-frequency displacement amplitude spectra of seismograms recorded at HAVO stations. To achieve this, we integrated the $k_0$ parametric correction into the SourceSpec code. We applied this correction to a test dataset consisting of 72 microearthquakes from the natural Castelsaraceno sequence, which occurred in August 2020 in the southwestern sector of HAVO. Using S-wave corrected spectral inversion, we observed that the cut-off frequency of 10 Hz previously estimated in uncorrected spectra of earthquakes with $M_W < 2.0$, was no longer recognizable. Additionally, the threshold for estimating reliable corner frequency decreased by almost an order of magnitude, from $M_W = 2.0$ to $M_W = 1.2$. Furthermore, after $k_0$ correction, earthquakes with $M_W < 1.5$ also align with the 0.1 MPa stress-drop curve, and the $f_C$-$M_0$ scaling approaches conditions close to self-similarity. We, therefore, propose that smaller earthquakes with $M_W \approx 1.5$ may follow a different physical mechanism, as they exhibit stress drop values around 0.1 MPa—an order of magnitude lower than those of events with $M_W > 2.0$.

## AS25-0466

# An examination of ZTD irregularities associated with volcanic eruptions and major seismic occurrences

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Alterations in atmospheric conditions lined to volcanic eruptions and seismic activities widely recognized and accepted. In this study, we investigate the Zenith Total Delay (ZTD) during a volcanic eruption and two significant earthquakes to identify anomalies in ZTD during these natural occurrences. In the first instance, fluctuations in ZTD during these natural occurrences. Fluctuations in ZTD values were detected over East Antarctica from February 19 to March 8, 2009, coinciding with the eruption of Mt. Chaiten volcano. These fluctuations exhibited a strong correlation with the unusual levels of atmospheric black carbon (BC) recoded in Antarctica during this timeframe. Consequently, we propose that the elevated ZTD values may have been influenced by substantial influx of BC into the atmosphere. We hypothesize that the massive eruption of Mt. Chaiten on February 19, 2009, served as the sources of the BC, which subsequently travelled from the volcanic front to the East Antarctic margin via the circular current. In the second instance, we examine the changes in ZTD associated with the two major earthquakes in the Himalayas, specifically the Chamoli earthquakes in 1999 and the Nepal earthquake in 2015. We analysed the ZTD derived from GPS data collected at the HYDE International GNSS Service (IGS) station. The ZTD values, which are sensitive to tropospheric weather conditions, exhibited a significant decrease during and after the earthquakes. Therefore, both volcanic eruptions and large earthquakes are likely contributors to the observed changes in ZTD.

## AS25-0469

# Source parameter estimation from local earthquakes in central and eastern Himalaya: An investigation into orogenic segmentation

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Orogenic segmentation across the arcuate Himalayan belt complicates deformational trends beyond central Nepal. Here, we attempt to discern the implications of spatially varying deformation on seismic hazard potential in eastern Nepal, Sikkim and Bhutan Himalayas. A comprehensive catalogue of 2,018 local earthquakes recorded during past deployments is utilized to estimate source parameters from P and S-wave spectra. Results indicate stress drop($\Delta\sigma$) and moment magnitude exhibit scaled dependence with linearly increasing relation. Scaling traced between seismic moment and corner frequency($M_0 \propto f_c^{-3}$) indicates no breakdown of earthquake scaling law for small earthquakes, thus holding potential to be scaled for modelling large earthquakes in the region. Empirical relationships established ($M_w$=0.55$M_l$+1.43,$M_w$=0.68$\log_{10}(M_0)$-6.20;$M_w$=0.61$M_l$+1.33,$M_w$=0.66$\log_{10}(M_0)$-6.06; and $M_w$=0.66$M_l$+1.37,$M_w$=0.66$\log_{10}(M_0)$-5.94) can serve as input for seismic hazard assessment in eastern Nepal, Sikkim and Bhutan. Spatial variability of $\Delta\sigma$ is reflective of high coupling along the Main Himalayan Thrust(MHT), high strain rate and lower seismic activity in eastern Nepal and Bhutan. Strike-slip faulting in Bhutan releases higher $\Delta\sigma$(~7–15 MPa) as compared to thrusting in Nepal releasing lower $\Delta\sigma$(~2 MPa). Low coupling along MHT in Sikkim substantiated by frequent release of stress through high seismic activity impedes low $\Delta\sigma$(~2 MPa). Beneath MHT, high radiated energy estimates($9\times10^{11}$ Nm) evidenced a high degree of heterogeneity except for eastern Nepal($8\times10^{7}$ Nm). Thus, eastern Nepal and Bhutan have the potential to experience a great earthquake, while Sikkim is susceptible to hazard due to active deformation along a multi-fault system. Consensus of spatial variation of source parameters with interseismic-coupling, strain rate and deformation mechanism indicates orogenic segmentation has crucial implications on seismic hazard potential.

## AS25-0489

# Long term precursory fault activation of the 2019 Mw 5.0 earthquake in the Weiyuan Shale Gas Field, Sichuan, China

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Anthropogenic activities such as hydraulic fracturing (HF) can trigger destructive earthquakes, the triggering mechanisms of which are still in debate. We utilize near-fault seismic recordings to study the preparatory phase of the 2019 *ML* 5.6 earthquake in the Weiyuan shale gas field (WSGF), Sichuan Basin, China, which struck 3 months after stimulation completion. This is one of the largest HF-triggered earthquakes worldwide. We observed an 11-month-long precursory fault activation, during which continuous seismicity illuminated the fault plane and provided warnings for a potential destructive earthquake. The fault activation is a consequence of injections in multiple HF well pads, with a variety of mechanisms at play. Numerical simulation reveals that the occurrence of the mainshock involves stress perturbation from post-injection aseismic slip. This work promotes our understanding of HF-induced earthquakes and suggests incorporating long-term near-fault observations and taking post-injection aseismic slip into account for effective hazard management.

## AS25-0502

# Focal mutheechanism and seismogenic structure of the 2024 Ms5.0 Muli earthquake swarm in Sichuan, southwestern China

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Onaaa 27th May 2024, an *M*s5.0 earthquake hit Muli, Sichuan, southwestern China, followed by subsequent *M*s4.4, *M*s4.5, and *M*s4.1 earthquakes in the next few hours. This earthquake swarm occurred in the western segment of the Muli arc belt within the Sichuan-Yunnan block, eastern margin of the Qinghai-Tibet Plateau. The nearest fault is a NW-trending Boke thrust, approximately 7 km away from the epicenter of the *M*s5.0 mainshock. To determine the seismogenic structure of the swarm, we used machine learning method and relocated the sequence based on waveform records from the regional networks and nearby reservoir networks, and then applied waveform inversion methods to obtain the focal mechanism solutions and centroid depths for 11 *M*s≥3.0 earthquakes in the sequence. We have identified and relocated more than 3000 events, including 226 foreshocks limited in a local area and around the *M*s5.0 mainshock. The spatial distribution of the relocated events shows the seismogenic fault striking along NNE direction with a high dip-angle plane dipping towards SE. The centroid depth of the *M*s≥3.0 earthquakes in the sequence ranges from 4.0 to 13 km, coinciding with the relocated result, which indicaties that the sequence occurred within the brittle layer of the upper crust shallower than the depth of 13 km. The focal mechanisms of the *M*s≥3.0 earthquakes are strike-slip faulting, except four with some normal component. Obviously, the Boke fault is not the seismogenic one. The above findings reveal that the seismogenic structure of the swarm is a blind high-angle left-lateral strike-slip fault along NNE direction.

## AS25-0585

# Sequence Characteristics and Seismogenic Structure of the 2025 Xizang Dingri M 6.8 Earthquake

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In this study we use continuous waveform data and seismic phase reports from the China Earthquake Networks Cente to detect and supplement the sequence of the January 7, 2025, M 6.8 Xizang Dingri earthquake using deep learning methods. The sequence, relocated via the double-difference method, occurred on the Dengmocuo Fault within the Shenzha-Dingjie Rift, extending 100 km north-south and 40 km wide, with depths ranging from 3 to 30 km. The fault plane is nearly vertical, slightly northwest-inclined. The foreshock sequence started ten days before the mainshock and showed a migration pattern towards the mainshock epicenter, with the migration speed accelerating to about 3 km/h one hour before the mainshock. It is hypothesized that the foreshock sequence have occurred on a blind minor conjugate fault, triggering the mainshock. We also calculated focal mechanism solutions using polarity data (M3–4), local seismic waveform fitting (M>4) and W phases (mainshock). The dominant solutions are normal faulting, consistent with the tectonic setting.

The rapid magnitude of the mainshock was M6.8, lower than the moment magnitude 7.1, a rare occurrence in Chinese mainland. Analysis of 260 earthquakes since 2013 reveals a linear relationship between Ms and Mw, with regional variations: Qinghai-Xizang Plateau earthquakes typically have larger Ms than Mw, while some along the plateau margin and Tarim Basin show the opposite. Our study provide scientific insights into the earthquake preparation process and mechanism of the 2025 Dingri earthquake, and offer valuable references for understanding the deformation mechanism and seismic hazard of the Qinghai-Xizang Plateau.

## AS25-0625

# Spatio-temporal analysis of source parameters in the East Anatolian Fault Zone, Türkiye

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On February 6, 2023, a seismic sequence struck southern Türkiye and western Syria along the East Anatolian Fault Zone (EAFZ), producing 2 major earthquakes: a moment magnitude ($M_W$) 7.8 earthquake along the Nurdağı-Pazarcık fault and a $M_W$ 7.6 earthquake occurred northeast of the first shock, in Kahramanmaraş province, involving the Sürgü and Çardak faults.

The aim of this study is to extract the source parameters of the EAFZ (e.g. $M_W$, seismic moment $M_0$, corner frequency $f_c$ and stress drop $\Delta\sigma$) to investigate ground motion variability before and after the seismic events of February 2023.

In a first step, we constructed a high-quality data set of low-to-moderate magnitude events ($2.0 <= M_L <= 5.5$) along the EAFZ main segments in the period from 01/01/2019 to 29/02/2024.

Next, we applied a non-parametric Generalized Inversion Technique (GIT) to isolate source, propagation, and site contributions to the Fourier Amplitude Spectra (FAS) for 9,442 events recorded by 173 stations. The GIT was applied over a frequency range of 0.5 to 25 Hz and the source spectra were found to be flat even at high frequencies (>10 Hz).

We then mapped potential proxies for intercepting the preparatory phase of the big earthquake (e.g., seismic efficiency) and reported differences in the average $\Delta\sigma$ between the Nurdağı and Sürgü segments. Interestingly, the $\Delta\sigma$ calculated over a given depth range increases with depth and appears to change significantly before and after the February 6, 2023 seismic doublet.

## AS25-0657

# Observation of repeating earthquakes on the edge of rupture zone of the 2008 Gyeryongsan, Korea, MW 3.6 earthquake

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Repeating earthquakes (REs) are a series of earthquakes that result from the repeated rupture of the same fault patch, sharing similar magnitudes and mechanisms. They have been observed in various tectonic environments, predominantly at plate boundaries where fault creep is evident, and are of great importance as they can provide fault slip rates at depth. REs have also been identified in intraplate regions, though their occurrence and characteristics remain less well understood.

In this study, we report the occurrence of REs in the Gyeryongsan region of the Korean Peninsula, a stable intraplate setting approximately 700 km from the nearest plate boundary. The Mw 3.56 earthquake occurred near Daejeon Metropolitan City on October 29, 2008, and our analysis of relative locations and source time functions indicates that the mainshock ruptured toward 126.99°, with subsequent earthquakes aligning in the same direction.

Notably, we identified an RE family consisting of 10 events between 2010 and 2019, occurring on the edge of the rupture zone of the 2008 Mw 3.56 Gyeryongsan earthquake. These REs began approximately two years after the mainshock and continued intermittently for over a decade. We interpret this activity as occurring within the damaged fault zone created by the 2008 event, reflecting extremely low loading rates of aseismic slip or slow stress accumulation in the intraplate region.

## AS25-0658

# Scaling of Fracture Energy in Earthquakes: Does It Correlate with Slip or Slip Squared?

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Understanding earthquake rupture growth and seismic radiation is essential for advancing earthquake source physics and mitigating seismic hazards. While source parameter scaling laws provide key insights into rupture growth processes, existing physics-based models do not fully explain all scaling laws. This study tests whether spontaneous dynamic rupture models, incorporating hierarchical variations in fracture energy within a slip-weakening friction framework, can reproduce both well-established and less well-understood scaling laws. To achieve this, we integrate a renormalization procedure into three-dimensional dynamic rupture models based on the spectral element method, enabling efficient simulations of multi-scale rupture processes. Simulated earthquakes (M2 to M6) allow us to quantify scaling relationships, including seismic moment, source duration, magnitude-frequency distributions, moment growth, fracture energy, stress drop, and scaled energy. Our results show that modeled stress drops and scaled energy remain magnitude-independent, and that the source duration scaling aligns with observations. However, modeled fracture energy scales linearly with mean slip, contradicting previous observational studies suggesting a quadratic or nonlinear dependence with mean slip. Sensitivity analysis reveals that input friction parameters do not significantly affect this trend. By reassessing observational data, we identify biases in previous fracture energy and mean slip estimates. Applying model-based corrections, we find that fracture energy scales linearly with mean slip across 10 orders of magnitude. These findings have important implications for understanding the energy budget of small and large earthquakes and the mechanisms governing rupture growth on natural faults.

## AS25-0660

# Stress and deformation state assessment through focal mechanism inversion and GNSS data in San Salvador, El Salvador

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El Salvador is located in northern Central America. The study area includes the San Salvador Metropolitan Area (SSMA), in the center of the country, which has a high rate of seismic activity as it is part of the El Salvador Fault Zone (ESFZ). In this study, the stress and deformation regimes are described. Maps of tectonic stresses and deformations have been developed, based on the inversion of focal mechanisms and velocities from the Global Navigation Satellite System (GNSS). The results indicate that the transcurrent stress regime in the SSMA is responsible for the generation of lateral faults and combinations of them, which interact with each other in the area and generate destructive earthquakes. They also reflect that in the SSMA the tectonics is governed by regional stresses, with σ1 in NW-SE direction and σ3 in NE-SW direction, unlike the San Salvador volcano and the Ilopango caldera that present a rotation of stresses, due to magmatic bodies present. Deformation analysis showed NE-SW oriented extension axes and NW-SE shortening axes for the whole study area, in addition to higher extension rates between San Salvador volcano and Ilopango caldera (0.35 µstrain/y), and right lateral shear axes with predominant E-W direction. Consequently, the deformation in the study area seems to respond mainly to the regional stress tensor, and not to the local stresses present in the volcanic structures. The results are intended to be essential inputs for hazard and seismic risk assessment of the SSMA.

## AS25-0674

# Near-field seismic observations of slip pulse durations and rupture stopping phases from large continental earthquakes

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Whether seismic slip in natural earthquakes propagates as a narrow pulse (short rise time) or crack (long rise time) is a fundamental question in seismology. There is compelling evidence from many large earthquakes that demonstrates that on average, local rise times are short compared to total event duration (~10–20%), thus supporting a pulse model. What is not clear, however, is the mechanism responsible for slip arrest. Does slip arrest occur due to the local frictional properties of the host fault (self-healing) or is the slipping fault arrested by the dynamic stress field returning from the fault edges (stopping phase)? To address this issue, we take advantage of the recent abundance of seismic observations from large continental earthquakes (Mw 7–8) to generate a catalog of slip-parallel ground velocity pulses in the near-field of the slipping fault (<3 km). Informed by dynamic rupture models, these records suggest slip rise time on the fault is short (1–9 s) and is arrested by stopping phases originating from low velocity layers near the surface, and from lateral fault boundaries. Records from elongated strike-slip ruptures show the influence of rupture segmentation. Slip and rise time near the segment boundaries are truncated by the arrival of stopping phases, and are larger near the center of the fault segments, consistent with a crack model of rupture. We suggest that for large continental earthquakes, short rise times, and thus pulse-like rupture behavior is controlled by the propagation and arrest of crack-like rupture cascade across segmented fault networks.

## AS25-0683

# Centroid Moment Tensor analysis of small earthquakes in Western Australia using WA and SWAN arrays

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The Western Australia Array (WA Array) and the Southwest Australia Seismic Network (SWAN) are seismic networks designed to investigate the composition, structure, and seismic activity of Western Australia. The WA Array, a large-scale 10-year project led by the Geological Survey of Western Australia, deploys 165 seismometers annually in a grid pattern. The SWAN network, a temporary broadband array of 27 stations, operated in Southwest Australia from mid 2020 to 2023 and recorded significant seismic activity including the Arthur River swarm which comprises over 3000 located events that began in December 2022 with the largest event MLv 5.2.

We present a Centroid Moment Tensor (CMT) analysis of small-magnitude earthquakes (Mb ≥ 3.7) detected within these networks, demonstrating the feasibility of resolving source mechanisms at lower magnitudes than typically studied. Our methodology involves full waveform modeling in a 4D spatiotemporal grid search allowing for variations in centroid location, depth and moment tensor parameters. Our initial analysis of earthquakes recorded by the SWAN array especially in the Arthur River swarm zone reveals a reverse faulting mechanism at a depth of approximately 1 km providing insight into the stress regime of the region.

By testing various frequency bands, we validate that the local Earth model developed from SWAN data using body waves adequately simulates seismic wave propagation up to 0.15 Hz. Successful CMT inversion of these small-magnitude events enhances understanding of seismic sources in Southwest Australia, aiding regional stress assessments and seismic hazard mitigation efforts in Western Australia.

## AS25-0689

# Characteristics of earthquake sequences on oceanic transform faults in the Northeast Pacific Ocean

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A significant portion of slip along oceanic transform faults (OTFs) occurs aseismically, but the relationship between seismic and aseismic slip remains poorly understood. Monitoring earthquake swarms and foreshock-mainshock-aftershock sequences along OTFs could potentially reveal how these two modes of slip interact. We will present results regarding such earthquake sequences along OTFs in the Northeast Pacific Ocean based on analysing continuous data recorded by ocean-bottom and near-shore seismometers. We will further discuss what the observed characteristics of these swarm, foreshock, and aftershock sequences might reveal about the properties of different aseismic slip modes (e.g., preslip, afterslip, slow-slip events etc.) on OTFs through the earthquake cycle.

## AS25-0747

# Source rupture characteristics of the Mw 5.3 Bhachau earthquake in the Kachchh intra-continental seismicity region

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The earthquake rupture properties are important to understand the earthquake dynamics, fault behaviour and seismic hazard assessment. However, obtaining the rupture properties of small-to-moderate earthquakes is challenging. The second moments theory helps solve this problem of estimating rupture properties of small-to-moderate earthquakes. In the present work, we used the second moments theory to study the rupture dynamics of a moderate-sized earthquake that occurred during 2020 in the Bhachau area of the Kachchh intra-continental seismic zone. The 2020 Bhachau earthquake of $M_w$ 5.3 is the only M> 5.0 earthquake to occur in this region since 2012 and also the epicentral region of the 2001 Bhuj earthquake of M 7.7. Utilizing the data from a dense seismic network and a seismic array, we obtained an area of 4.31 $km^2$ with the characteristic dimension of 1.56 km x 0.88 km for this event. The characteristic rupture duration and rupture velocity are estimated to be 0.36 s and 2.53 km/s, respectively. This study reveals a partially unilateral directivity towards the northeast, which is well-consistent with the spatial evolution of the aftershock activity, where the majority of the aftershocks occurred in a linear pattern trending northeast. Based on the present study with rupture properties and spatio-temporal evolution of aftershocks, we infer that the 2020 Bhachau earthquake occurred at the juncture between the Kachchh Mainland fault and South Wagad fault and propagated northeast, activating the North Wagad fault; it further reveals the interconnected and complex nature of the tectonics in this region.

## AS25-0770

# High-Resolution Analysis of the ongoing seismic sequence in the Aeolian Archipelago, Southern Italy

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In February 2025 a seismic sequence started in the western portion of the Aeolian Archipelago (south Tyrrhenian), an area mainly controlled by the NW-SE convergence between African and European plates. The largest event ($M_w$ 4.7) occurred on February 7, located ~10 km south of the Alicudi Island and ~40 km off the coast of Sicily. The sequence, to date still ongoing, allows the investigation of seismogenic processes in this offshore area, where a seismic potential of ~M7 has been suggested. However, analyzing offshore seismic sequences pose significant challenges due to the lack of local stations and the asymmetric network configuration. We employed advanced methods to overcome these challenges and improve the characterization of the seismicity. We first performed single-station analysis at the two closest stations, applying a machine-learning approach to detect weak earthquakes and to pick P- and S-wave arrival times. We then combined location techniques based on Bayesian Inference and Distance Geometry Solvers with a probabilistic inversion tool for seismic source characterization. Our analysis allowed the identification of 133 seismic events, compared to 43 of the Italian bulletin. Moment tensor solutions were estimated for the two largest earthquakes indicate reverse faulting mechanisms along a ~SW-NE oriented fault, which is in agreement with the spatial distribution of the epicenters. A high waveform similarity among earthquakes in the seismic sequence suggests that this was the predominant mechanism of the entire unrest. The characterization of the seismic activity and fault geometry is essential to improve seismic and tsunami hazard assessment and mitigation.

## AS25-0777

# Bayesian source inversion of low-frequency events in the Himalaya

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Low-frequency seismic events are crucial for revealing slow, long-duration, and transient processes that conventional high-frequency analyses tend to overlook. The convergence of the Indian and the Eurasian Plates, which gave rise to the Himalaya and the Tibetan Plateau, represents a region of high-strain accumulation, complex fault interaction and dynamic geomorphic processes. It is an excellent setting for studying such events and understanding the inherent complex processes. The semblance technique, which measures waveform coherence across seismic arrays, offers a robust means to detect these subtle low-frequency signals in noisy environments. In this study, we identify a few low-frequency events which are located in different parts of the Himalaya and classify their geophysical nature. We extend conventional centroid single force and moment tensor inversion techniques by incorporating a Bayesian bootstrap resampling framework, thereby systematically quantifying the uncertainties associated with the estimated source parameters. This advanced inversion framework enables us to resolve both shear (double-couple) and non-shear source components, thereby facilitating the discrimination between tectonic earthquakes and geomorphic processes such as landslides and glacier dynamics. Our approach not only contributes to the development of a low-frequency seismic catalogue for the Himalaya but also contributes towards a better understanding of the underlying geodynamic processes associated with these events.

## AS25-0840

# Stress drops of intermediate-depth intraslab earthquakes beneath northeastern Japan

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We calculated stress drops for ~4500 small magnitude (2.0<M<5.0) intraslab earthquakes at intermediate depths beneath Tohoku, northeastern Japan from 2003 to 2023, using corner frequencies of earthquakes estimated by an S-coda-wave spectral ratio method. Similar to the results in Hokkaido, the median stress drops in the oceanic crust (OC) are about half those in the oceanic mantle (OM). The median stress drops in the OC decrease from depths of 70 to 120 km but switch to increase from 120 to 170 km. These results suggest that the rigidity in the OC decreases and then increases with depth due to combined effects of the dehydration associated with the eclogite formation and the increasing temperature with depth. These depth variations are consistent with results of the previous study beneath Hokkaido, but the median stress drops in the oceanic plate beneath Tohoku are generally smaller than those beneath Hokkaido. Considering observational previous studies of b-values of earthquakes and seismic velocities structures, our stress drop results suggest that differences in the degree of hydration of the oceanic plate in the near-trench regions could produce the different behaviors of in-slab stress drops at intermediate-depth observed in Tohoku and Hokkaido. We also find that the median stress drops for the OC at depths of 70 to 90 km beneath Miyagi and Fukushima prefectures after the 2011 M9 Tohoku event tend to be slightly larger than the stress drops prior to it. Thus, intermediate-depth intraslab earthquakes may reveal interactions between slab stresses and earthquake source properties.

## AS25-0844

# Independent catalogs of moment magnitude and seismic source parameters in Northeastern Italy

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The study of moment magnitude ($M_W$) and seismic source parameters is essential for understanding seismicity and earthquake rupture processes. This study presents an independent $M_W$ catalog and seismic source parameters for earthquakes in northeastern Italy (Lat. 10.0°–14.5° N, Long. 44.5°–47.0° E) recorded from 2016 to 2023 by the OGS network (OX) and neighboring seismological networks. $M_W$ values ($0.50 \leq M_W \leq 3.95$) are derived from response spectra (SA) at 0.3 s and 1.0 s using empirical relationships specifically tuned for the study area. An $M_W$–$M_L$ relationship for Northeastern Italy was also established. Source parameters, including seismic moment - $M_0$, corner frequency - $f_C$, source radius, radiated energy - $E_R$, static and apparent stress, seismic efficiency, are estimated for well-constrained events using a parametric modeling approach (SourceSpec), and the trends of the $f_C$-$M_0$ and $E_R$-$M_0$ conditions are analyzed. Results indicate that $f_C$-$M_0$ relationship approaches conditions close to self-similarity, with static stress drop values mostly between 0.1 and 10 MPa. These findings, collected in open-access catalogs, enhance our understanding of seismic source properties in the region, with implications for seismic hazard assessment, tectonic modeling, and ground motion models.

## AS25-0920

# Earthquake stress drop evolution during the recent Fentale-Dofen (Ethiopia) and Santorini-Amorgos (Greece) sequences

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The determination of earthquake stress drop during seismic sequences aids in understanding the nature and dynamics of mechanisms driving the seismicity. For example, when seismicity is driven by fluid intrusion, low stress drops are expected in the early stages as the elevated pore pressure reduces the effective normal stress. In 2024–2025, two major seismic sequences have taken place, both associated with large aseismic deformation: the Fentale-Dofen (Ethiopia) sequence starting in September 2024, and the Santorini-Amorgos (Greece) sequence starting in January 2025. The Fentale-Dofen sequence is clearly driven by magmatic intrusion along the East-African rift while the origins of the Santorini-Amorgos sequence remain debated. We first analyze these sequences using a station-pairs template matching technique, that simultaneously detects earthquakes (not necessarily co-located with their templates) and characterizes their relative stress drops. For both sequences, several hundreds of earthquakes with similar focal mechanism are characterized, most of them with moment magnitude above 3.5. For the Santorini-Amorgos sequence, the detections are further associated with catalogs based on arrival times (Lomax et al., 2025) in order to explore the relations between depth and stress drop. We also compare the stress drop values with those obtained from P-wave and S-wave displacement spectra. Preliminary results show that most of the low stress drop values are observed in the early stages for both sequences, and that large stress drop values are usually observed during the most seismically active periods.

## AS25-0930

# New formulation reduces the scatter of earthquake stress drop estimation

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Stress-drop is the overall reduction of average stress due to energy release during an earthquake, and should reflect geometrical, rheological and dynamic properties of the seismic source. Stress-drop values, estimated using seismological data, vary over four orders of magnitudes making the stress-drop an enigmatic parameter. There have been many efforts to reduce the stress-drop scatter, focusing mainly on observational aspects, in which source properties such as, corner-frequency and seismic moment were measured, considering site, path and additional source properties. Standard cubic power-law relation between corner-frequency of radiated waves and stress-drop, with a constant coefficient *K,* is and additional reason to its significant scatter. We provide a new formulation, applying a strain-drop dependent *K*; by that leading to a significant reduction of the relation of stress-drop to corner-frequency, down to a power-law of 3/4. Results based on a wide range of theoretical, laboratory and observational measurements demonstrate that the new formulation significantly narrows the three-to-four orders of magnitude of scatter, to about one order of magnitude of ~*10 MPa*. The more converged range of stress-drop values, obtained by the suggested new formulation, may be used to support those who argue for self-similarity of earthquakes. In summary, the impact of the uncertainties of the source properties, seismic-moment, $M_0$, seismic-potency, $P_0$, and corner-frequency, $f_C$, on the value of stress-drop is not as dramatic as so many studies argued before. Furthermore, as we demonstrate, the reduction of scatter does not eliminate internal trends, controlled by geometrical, rheological and dynamical properties at the source.

## AS25-0969

# Seismic source and fluids in the Mefite d'Ansanto deep-CO2 degassing area (Southern Apennines, Italy)

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The Mefite d'Ansanto is one of the world's largest non-volcanic $CO_2$ degassing sites, located in the axial zone of the Southern Apennines (Italy), at the northern tip of the fault system responsible for the devastating 1980 $M_W$ 6.9 Irpinia earthquake. This region is characterized by NW–SE normal faults that are preferred pathways for deep fluids to ascend to the surface, thus affecting stress axis distribution and seismic activity. Fluids, rock anisotropy and porosity play a fundamental role in the earthquake mechanics by changing pore pressure, fault strength, and rupture dynamics. To investigate these processes, we analyze the full moment tensor solutions of earthquakes recorded in the Mefite area as part of the multidisciplinary FURTHER project (https://progetti.ingv.it/en/further), a collaborative initiative exploring the role of fluids in seismogenesis within the Southern Apennines. Our study utilizes high-quality seismic data (~300 earthquakes, $M_{max}$ = 3.3) collected during a two-year temporary passive survey. Keeping in mind that crack opening and closure may induce significant non-double-couple (NDC) components of the seismic moment tensor, we compute the double-couple (DC), isotropic (ISO), and compensated linear vector dipole (CLVD) components of the moment tensor solutions. Results are analyzed in both spatial and temporal domains to gain deeper insights into the fluid-seismicity relationship and improve our understanding of fault mechanics in the Southern Apennines.

## AS25-0985

# Full Moment Tensors and Uncertainties assessed for West Iberian Earthquakes

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Western Iberia is located in a region undergoing slow deformation, with both its onshore and offshore areas prone to earthquake generation. Within the Western Iberia mainland, considered as a stable continental crust, some of the strongest intraplate earthquakes of Europe took place. The 1531 M6.5–7.1 Lisbon, the 1858 M7.1 Setúbal, and the 1909 M6 Benavente earthquakes are examples of these intraplate events. On the other hand, the SW Iberia Margin depicts a complex tectonic setting where plate motion is accommodated along a distributed fault network rather than along a single plate boundary. These faults were associated with large historical earthquakes and tsunamis in the region, such as the 1755 M8.75 and the 1969 M7.9 earthquakes.

To enhance our understanding of earthquake processes in the Western Iberia, we calculate full moment tensor for earthquakes with magnitudes Mw> 4.0 that occurred in Portugal using complete broadband waveforms recorded by the Portuguese National Seismic Network. We assess tensor uncertainties by applying ISOLA2024 software and its recent upgrades in a typical frequency range of 0.03–0.09 Hz. We focus attention on possible non-shear faulting, either real or apparent, and seek its explanation. We determine the moment-tensor solution of the shallow Mw4.4 earthquake that occurred on 17$^{th}$ February 2025, which is interpreted as a reverse fault, aligning with the compressive tectonics of the region. Our outlook is to implement full moment tensors with uncertainties in routine practice.

## AS25-1001

# Geodynamics along the western part of Africa-Eurasia plate boundary from focal mechanisms inversion

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Complex deformation is observed along the plate boundary between the Africa and Eurasia plates, this complexity is highlighted by the faulting mechanism changing from normal faulting at the Mid-Atlantic Ridge to thrust and strike-slip faulting in the Ibero-Maghreb region (Iberia, Morocco, Algeria and Tunisia). The geodynamics of the study area shows the occurrence of NW–SE convergence between the two plates, with anticlockwise rotation. An updated scheme of the pattern of the tectonic stress direction from the Azores Archipelago to the Tunisian Atlas is presented, along with the analysis of the principal stress axis orientations ($Sh_{max}$, $Sh_{min}$) from the inversion of fault plane solutions. We used a catalogue of 557 fault plane solutions with only main shocks for the period from 1931 to 2020 considering only the earthquake mechanisms of events $4.0 \leq M \leq 8.4$. The present work includes the area from Tunisia to the Mid-Atlantic Ridge. We used the Slickenside analysis package of Michael's method. The stress field we obtained shows an extensional regime in the Mid-Atlantic Ridge, Terceira Ridge and Azores Islands and a strike-slip regime along the Gloria Fault, Gorringe Bank and Gulf of Cadiz, to southern Spain. The same regime is also observed in the Rif and Alboran Sea. The stress regime becomes compressional in western Algeria, with strike-slip in eastern and southern Tunisia and an exception in northern Tunisia, where the stress exhibits a reverse rupture process.

## AS25-1025

# Seismicity and static stress changes modeling for the 2023 Gorj Romania, earthquake sequence

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The purpose of this study is to understand the seismic interactions for a crustal earthquake sequence started with a magnitude Mw4.8 foreshock on February 13, 2023, followed by the Mw5.4 mainshock on February 14, 2023, in the Targu Jiu area, Gorj prefecture, in the southwestern part of Romania. We performed static Coulomb Failure Stress change analysis to check whether the foreshock may have had any role in triggered the mainshock. Next, we estimated the ETAS model parameters for the sequence using the ROMPLUS earthquake catalogue provided by the National Institute for Earth Physics, between February 13, and March 23, 2023, with magnitudes Mw from 2.1 (to account for possible partial incompleteness) to 5.4 and depths between 1.4 and 26.3 km. Since the ETAS model is sensitive to changes in the magnitude of completeness over time, we adopted a variable magnitude of completeness approach, through bootstrapping. Both sets of parameters were optimized for the entire sequence, beginning from the foreshock event. The optimization aimed to discern whether the mainshock originated from "external" factors, like tectonic loading, or from stress transfer resulting from the previous seismic events. The outcome of these assessments consistently indicated a low background probability for the mainshock. This observation suggests that the foreshock event significantly contributed to the triggering of the mainshock, a finding that aligns with the changes in the static Coulomb Failure Stress.

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## AS25-1041

# Improving earthquake depth resolution in global seismic catalogues

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Earthquake depth remains an enigmatic and often poorly constrained parameter in much of the global seismic record. For earthquakes that occur within dense seismic networks reliable depth estimations are possible. When outside the network, even by a small distance, earthquake depths become ambiguous. For relatively deep earthquakes (> 28 km depth), the lack of depth resolution from nearby stations can be mitigated using reported depth phases. The International Seismological Centre (ISC) regularly augments the reported phases by adding additional targeted depth phases picks, adding depth resolution to thousands of remote earthquakes. This approach however cannot be applied to all earthquakes and fails for moderate magnitude shallow earthquakes where the surface reflected depth phases are subsumed within the earthquake source time function. By jointly solving for the earthquake depth, source time function and moment tensor with the International Seismological Centre Probabilistic Point Source Modelling (ISC-PPSM) methodology, we can gain new constraints on the depths of many shallow moderate magnitude earthquakes. Here we evaluate the depths determined by these complimentary methodologies, as well as comparing with depths obtained using other methodologies such as moment tensor inversions using low pass filtered waveform data and seismic slip models derived from seismic or geodetic data. We consider local and regional network geometries that permit reliable earthquake depth determination in well instrumented areas and consider how reliable tele-seismic depth determinations using depth phases can be improved and extended to a wider spectrum of earthquakes through the use of virtual arrays.

## AS25-1047

# The February 2023 Târgu Jiu Seismic Sequence: Rupture Dynamics, Stress Field, and Fault Network Interactions

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The February 2023 Târgu Jiu seismic sequence provides key insights into fault network dynamics and stress field characteristics in the Oltenia region of Romania. The sequence started with a foreshock (Mw=4.9) on February 13th, followed by a mainshock (Mw=5.4) on February 14th, followed by ~4100 aftershocks. Events occurred at depths of 10–20 km, affecting ENE-WSW trending extensional faults at the contact between the Getic Depression and the Southern Carpathians.

To investigate the rupture process and stress interactions, we employed a multi-method approach, integrating high-resolution hypocenter relocation, first-motion polarity focal mechanisms, waveform inversion, and moment tensor solutions. Additionally, we utilized a self-similar dynamic rupture model based on the simplified wave-rupture analogy, which offers an efficient and computationally feasible approach for simulating complex rupture scenarios. This method decouples the fracture front propagation from slip calculations, allowing for a more flexible modeling of stress interactions and rupture dynamics within the fault system.

Our findings indicate a multi-fault rupture scenario, characterized by variable slip distributions and significant stress transfer between fault segments. The stress field reveals an extensional regime ($\sigma 1$ nearly vertical), with a maximum horizontal stress (SHmax) oriented NNE-SSW, consistent with the observed normal faulting mechanisms ($R' \approx 0.5$). By combining seismic observations with a self-similar rupture model, we provide new insights into the interplay between inherited crustal structures and seismicity distribution.

This research highlights the importance of integrating advanced modeling techniques with observational data to improve seismic hazard assessments.

## AS25-1050

# Near-real time estimation of source parameters and focal mechanisms for earthquakes in Romania: Insights from recent seismic events

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Accurate and rapid estimation of earthquake source parameters is crucial for understanding seismic activity and mitigating risks in seismically active regions such as Romania. This study presents an integrated approach for near-real-time estimation of earthquake source parameters, combining automated hypocenter determination, moment magnitude (Mw) calculation, and focal mechanism solutions. By utilizing a dense seismic network and advanced waveform inversion techniques, we enhance the precision of source characterization for moderate to large earthquakes. In this study we analyzed over 600 seismic events with ML≥2.5 recorded in the last decade in Romania.

The methodology includes real-time data acquisition from Romania's seismic monitoring networks, automatic processing of first-motion polarities, and moment tensor inversion to determine faulting mechanisms. The integration of focal mechanism solutions provides insights into the regional stress field and fault interactions, essential for seismic hazard assessment. The main goals are the independent estimation of the seismic moment and common characterization for all events recorded by the velocity network. This research contributes to the development of an efficient early-warning framework for Romania, supporting emergency response strategies and risk mitigation efforts. The findings also offer a deeper understanding of the seismotectonic environment, aiding long-term seismic hazard assessments.

## AS25-1124

# Temporal and stress analysis of the Lesotho/South Africa earthquake swarm: Integrating frequency-magnitude distribution and fault plane solutions

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From July 2019 till the present, there has been an increase in seismicity on the South-Western border between South Africa and Lesotho. Historically, there has not been any seismicity recorded in the area; most of the seismicity was due to the open cast mining and the construction of the Katse dam in Lesotho and sparse seismicity in the Karoo. There has not been a large event to consider the seismicity due to a main shock and aftershock sequence, implying that the seismicity represents an earthquake swarm. Studying this earthquake swarm will assist in understanding the fault dynamics and stress environment in the area. Using more than 1000 earthquakes, fault plane solutions were calculated, using FOCMEC and FPFIT in Seisan, for events of magnitude greater than or equal to $M_L$2.0. The major faulting in the area appears to be strike-slip, some reverse oblique-slip, and normal strike-slip. The b-value was greater than one from July 2019 to June 2024 and dropped to less than one thereafter. This suggests the possibility of higher stress in the area and could potentially be a precursor to a large event.

## AS25-1230

# Seismotectonic Characteristics of the 2020 Orșova Seismic Sequence, Southern Carpathians, Romania

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Seismic activity in the southwestern part of Romania is particularly relevant at the junction between the Southern Carpathians and the Moesian Platform. This transitional tectonic setting includes a complex network of faults and crustal heterogeneities, which occasionally generate moderate earthquakes. Although less active than the Vrancea zone, located at the contact of the Eastern with Southern Carpathians, the region is still of significant seismotectonic importance due to its potential for crustal seismicity and its role in accommodating regional tectonic stress between major structural units.

This study focuses on the analysis of a crustal earthquake sequence that occurred in the western part of the Southern Carpathians, close to Orşova city, between 25 June and 6 July 2020. The sequence was initiated by a foreshock ($M_L$ 3.4), followed by the mainshock ($M_L$ 4.5) at a depth of 16 km, and was accompanied by 16 aftershocks ($M_L$ 1.5–3.4). To better characterize the sequence, we applied advanced full waveforms inversion and spectral analysis techniques to estimate key source parameters, offering insights into the rupture processes and the seismotectonic background. The resulted source parameters will be integrated into an extended dataset, which will serve as a basis for deriving scaling relationships applicable to the broader regional seismicity.

This work was carried out within Nucleu Program SOL4RISC, supported by MCI, project no PN23360201.

## AS25-1246

# New analysis of InSAR and seismology for kinematic reconstruction of the 1995 offshore Aigion mw 6.2 earthquake (Greece)

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During the transition from early to mature rifting different fault geometries and kinematics may form. In particular it is debated whether low angle normal faulting occurs during early rifting. It is therefore crucial to constrain how faults slip during earthquakes by thoroughly exploring the variability of the fault models derived from geophysical observations. In addition, assigning earthquakes to particular faults is important for future hazard assessment.

We study the Mw 6.2 Aigion earthquake that occurred in the Corinth Rift, Greece on June 15, 1995, using InSAR and seismic waveforms. Corinth is a rift in its early stages, currently extending at a rate of up to 10–15 mm/yr in the N-S direction and characterized by normal faults defining a graben. The Corinth Rift can generate major destructive earthquakes, making it important to understand fault position and geometry. However, the subsurface geometry and position of the fault source of the 1995 earthquake is debated, including the dip orientation and angle.

The deformation field from InSAR shows up to x cm of ground motion on the north coast, but with significant deformation likely offshore. The modelling of only the InSAR result shows both a north dipping (33°) or south dipping (42°) normal fault, striking roughly east-west, fits the data; but with a slight preference for the north dipping fault. However, joint inversion of InSAR and teleseismic data favours a south-dipping fault (xx), in contradiction to the fault geometry used so far in the literature.

## AS25-1249

# Earthquake swarm activity in Felixlândia, Brazil

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On January 9, 2025, at 22:09:07 UTC, a magnitude 3.3 mR earthquake occurred approximately 18 km southeast of Felixlândia, Minas Gerais, Brazil. This event was followed by several aftershocks over the following days, with a total of 17 events recorded by the Brazilian Seismic Network (RS. Highlighting one event, on January 15, 2025, at 02:11:11 UTC (2.7 mR), That was reported by the public through the "Sentiu aí" platform of the University of São Paulo's Seismology Center. The regional Brazilian Seismic Network played a crucial role in monitoring these events, with approximately 15 stations contributing to the location of this seismic swarm. The largest event was located using 37 phases with 2 s of the residuals. The preliminary results show that the Brazilian Seismic Network detected 17 events in Felixlândia with magnitudes ranging from 1.9 to 3.3 mR. The waveform of these earthquakes are very similar, suggesting that they occurred in close proximity and likely share the same fault mechanism.

## AS25-1281

# Seismicity and Stress Regimes in Southern Tonga Slab: Evidence for Stagnation and Deformation in Mantle Transition Zone

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Tonga is a convergent plate boundary between the Pacific and Australian plates and is the fastest and the most seismically active deep subduction system in the world. We focused on southern Tonga (south of latitude 22° S) and the mantle transition zone (depths of 410–690 km), where seismic activity forms two subparallel bands of events in the east and west. We performed stress analysis by inverting focal mechanisms of earthquakes available in the Global Centroid Moment Tensor catalog and revealed two distinct stress regimes in the slab. While the stress orientation in the eastern slab segment conforms to the down-dip compressional stress along the entire slab, the stress orientation in the western slab segment is different, having the maximum compression in the vertical direction. This suggests that the western segment can represent a stagnant slab with flattening and bending, as proposed by modelling studies. Its connection with the younger actively subducting slab is supported by the horizontal westward shift at 520 km depth. The stress analysis also indicates substantially different fault orientations in both segments. In the actively dipping slab, the majority of activated faults are predominantly sub-horizontal. However, they are significantly inclined from vertical in the stagnant slab segment. A higher scatter in fault orientations in the stagnant slab suggests deformation, fragmentation and rheological complexity resulting from bending and flattening.

## AS25-1325

# Migration Analysis of the Lesotho/South Africa Earthquake Swarm: Implications for Fault Interaction and Seismic Triggering Mechanisms

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The ongoing seismic swarm in the Lesotho-South Africa region offers an interesting chance to explore how earthquakes migrate and how they interact with faults and various triggering mechanisms. In this study, we use a detailed catalog of earthquakes to examine how the swarm has evolved both spatially and temporally. Our initial findings reveal a clear migration pattern, with seismic activity spreading over distances greater than 50 kilometers in just nine months. When we analyze the larger earthquakes, we find they are spread throughout the swarm rather than concentrated in the area where it began. This suggests that the stress in the region is being redistributed rather than driven by a single factor. We also notice that the rates at which this migration occurs change, speeding up and slowing down at times. This variability hints at a complicated relationship between changes in regional stress and potential external influences, like fluid movements or aseismic slippage along faults. Distinct clusters are visible in 2024 around March, May, and August. These insights help us better understand the mechanisms behind seismic swarm activity in this intraplate area. Looking ahead, incorporating data from geodetic studies and analyzing the focal mechanisms of these earthquakes will enhance our understanding of how faults and external forces interact to contribute to the continuation of this swarm.

## AS25-1367

# Demonstration of clustering-based stress field analyses: insights from the Vrancea zone and the 2023 Turkey earthquake sequence

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We performed stress field analyses in the Vrancea zone (SE-Carpathians) and the 2023 Turkey earthquake sequence region using clustering-based inversions of focal mechanism solutions (FMS). We aimed to utilise a non-parametric unsupervised clustering algorithm originally designed for stress inversions (CluStress) to identify groups with homogeneous earthquake source mechanisms and support a more profound understanding of the tectonic setting in these areas. On the one hand, the presentation consists of previously published results from the Vrancea zone, indicating good agreement with pre-existing knowledge. On the other hand, with this methodology, preliminary results are shown for the region of the 6$^{th}$ February 2023 Kahramanmaraş Earthquakes, hoping to discuss further developments and applications with the audience.

## AS25-1414

# Source parameter determination with uncertainty estimate for seven earthquakes in the Adriatic Sea and its surroundings in Croatia and Italy

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The Adriatic Sea and its surrounding regions are tectonically active, experiencing moderate to strong seismicity due to the convergence of the European and African plates and the interaction between the Adriatic microplate and Europe. Reliable earthquake source parameters offer valuable insights into these complex structural settings. However, determining earthquake source parameters suffers uncertainty from data noise and theory errors mainly due to the simplified description of Earth's interior (structural error). This uncertainty is rarely treated in regional earthquake catalogues. Here, we use the point-source moment tensor (MT) to represent the earthquake sources, and use our evolving method to retrieve the MT parameters with accompanying uncertainties of small to moderate-size earthquakes in the Adriatic Sea and its surroundings in Croatia and Italy. The seven chosen events include five in Croatia: the 2020 5.4 Zagreb earthquake and its 4.9 aftershock, the 5.0 foreshock of the 2020 Petrinja earthquake, the 2021 5.2 central Adriatic earthquake, and the 2024 4.6 southern Adriatic earthquake, and two in Italy: the 2022 5.5 earthquake in Costa Marchigiana Pesarese and the 2023 4.9 earthquake in Marradi (Tuscany). Some of these events caught worldwide attention, in particular, the 2020 5.4 Zagreb earthquake. We treat the data and structural uncertainty within a hierarchical Bayesian framework. Our solutions are then compared with the INGV and other regional catalogues to demonstrate the method's feasibility and potential improvement in source determination after uncertainty estimate. The obtained source mechanisms will contribute to numerous other studies (e.g., numerical simulations, hazard assessments, and Coulomb failure analyses).

## AS25-1474

# Stochastic Finite-Fault Modeling of Near-Field Ground Motions: Integrating Radiation Directivity and Site-Specific Amplification Effects

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Rapid and accurate assessment of strong ground motion is crucial for seismic hazard response and engineering applications. The stochastic finite-fault method, which comprehensively considers source effects, path effects, and site effects, has been widely recognized as a physically reasonable and effective approach for high-frequency strong ground motion simulation. To enhance the usability and flexibility of this method in engineering practice, this study employs the advanced ground motion simulation software GMSS2.0 to implement stochastic finite-fault modeling and further optimize the characterization of the rupture process. The model incorporates the relationship between angular frequency and rupture velocity to more accurately depict rupture propagation characteristics. Additionally, to address the limitations of the stochastic finite-fault method in near-fault regions, particularly concerning fault scaling effects and rupture directivity, this study introduces a directionality-radiation-related correction coefficient, Drup, to improve near-fault ground motion simulations. The methodology is applied to the 2022 Luding Mw6.6 earthquake and the 2012 Ninglang Mw5.5 earthquake, with site amplification effects evaluated based on the horizontal-to-vertical spectral ratio(H/V). Comparative analysis of peak ground acceleration (PGA) and 5% damped pseudo-spectral acceleration (PSA) between observed and simulated values indicates that in complex terrain regions, the average H/V can effectively refine site amplification factors, while the Drup correction improves the representation of rupture directivity and topographic effects. The proposed approach enhances the reliability of ground motion simulations, providing more accurate seismic hazard assessments and improved predictions for earthquake-resistant design.

## S19 Thermochemical Heterogeneities in the Crust and Upper Mantle from Geophysical Approaches

### AS25-0135

# Thermal structure revealed by seismic Lg-wave attenuation beneath Anatolia and its implications for mantle upwelling and plateau uplift

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The Anatolian Plateau is experiencing rapid uplift and westward tectonic escape at the termination stage of oceanic subduction and the conversion to continental collision. The seismic velocity and attenuation structures can infer the crustal response to the transition of the subduction environment from eastern to western Anatolia. In this study, we collected 56,341 seismograms recorded at 650 stations from 521 regional crustal earthquakes between January 2000 and December 2020. To improve the signal-to-noise ratio and avoid the influence of complex rupture processes of large earthquakes, only earthquakes with magnitudes between mb 4.0 and 6.5 were used. Based on regional phase of Lg waves, we construct a broadband attenuation model with high-resolution of approximately 1.0° × 1.0° for the Anatolian Plateau to constrain lateral crust heterogeneities linked to the transition from oceanic-continental subduction to continental-continental collision. Crustal Lg attenuation links late Cenozoic magmatism with asthenospheric upwelling by characterizing the lithospheric thermal structure. Combined with previous studies, we suggest that the mantle upwelling induced by the delamination of the Bitlis slab is likely reworking the crust in eastern Anatolia and is the cause of widespread thermal anomalies there. The lithospheric dripping process in central Anatolia may facilitate the mantle flows through the window between the Cyprus and Aegean slabs, and results in piece-meal low QLg anomaly pattern in central Anatolia.

## AS25-0257

# Use of seismic coherence to detect zones of chemical and phase heterogeneity in the mantle predicted by mineral physics

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The coherence of seismic body waves, expressed by the fluctuation of amplitudes and travel times between closely spaced sensors, can be used to determine the depth and lateral dependence of the spatial spectrum of small-scale (10–100 km) scatterers in the mantle. Coherences make it possible to identify zones of scattering associated with previously undetected and poorly resolved changes in composition and mineral phase in Earth's mantle. Experimental and computational mineral physics predict that changes in mineral lattice structure of the mantle, due to changes in lateral temperature and composition, will be expressed by peaks in the power spectrum of seismic velocity heterogeneity in narrow ranges of depth. We exploit these predictions to interpret the compositional and phase variation of Earth's upper mantle from the spatial spectrum of seismic velocity heterogeneity determined from coherence measurements of teleseismic P waves recorded by dense arrays of seismometers deployed by the Transportable and Flex Arrays of Earthscope. Knowledge of this heterogeneity spectrum enables new constraints to be found on the history of Farallon plate subduction beneath North America and the compositional component of crustal and plate fragments that have been cycled through Earth's mantle.

## AS25-0435

# Lithospheric structure of North East India based on integrated geophysical petrological modeling

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In the North East India region (or NE India), two adjacent continental subduction zones exist where the Indian plate underthrusts beneath the Eurasian plate in the North and the Burmese plate in the East. The shallow crustal structures of the region have been extensively investigated, but the deep crustal and lithospheric features need to be investigated to understand the complex geodynamic setting of the region.

In this work, we investigate the thermochemical structures of the deep crust and upper mantle of NE India and its adjoining regions based on integrated geophysical petrological forward modeling. Our best-fitted 3D model, where the deviation between observed and modelled response of the topography and gravity anomalies is minimal shows two large-scale lithospheric provinces in the study region. The subcontinental lithospheric mantle of the southern Tibetan (ST) is associated with a Phanerozoic type, while NE India has a Proterozoic type composition. We find a transition of average crustal thickness of ~37 km in NE India to ~68 km in the ST region. Similarly, the thin lithosphere (~110 km) beneath the NE Indian plate thickens rapidly beneath ST (~225 km). The Shillong Plateau, which is a topographic high in the Himalayan foreland shows both anomalously thin crustal and lithospheric thickness. We speculate that these patterns reflect the effect of the Kerguelen plume, which is corroborated by geological observations.

Our current model offers a first-order discussion of the main tectonic features and their lithospheric imprint and serves as a base for future geodynamic studies of two-sided subduction settings.

## AS25-0611

# Determining the subsurface conditions of the crust and upper mantle using joint geophysical-petrological-lithological inversion

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Determining the nature of the crust and upper mantle is essential for geothermal resource assessment, resource exploration, hazard assessment and understanding tectonic processes. Focussing on geothermal resource assessment, variations in subsurface lithology and the associated thermal parameters will modify subsurface thermal structure, a parameter useful for geothermal exploration. Given subsurface temperature signals are intertwined with other variables, we require ways to separate the individual contributions in overlapping datasets. One such way is using a joint geophysical-petrological inversion scheme to invert different complimentary datasets for lithospheric thermochemical structure within a thermodynamic framework. The modelling approach first computes the geotherm by solving the heat conduction equation in the lithosphere for a given distribution of thermal conductivity and radiogenic heat production parameters. Then seismic and other geophysical data are inverted, directly for temperature. The output from the inversion includes the lithospheric geotherm, lithospheric thickness and Moho depth, as well as crustal structure (seismic velocity, density and radiogenic heat production), and radial anisotropy. The lithospheric geotherm is useful for determining heat in place and geothermal potential. The additional output can provide insights into the lithological and compositional variations in the crust. We further develop the workflow by introducing lithological boundaries from detailed 3D subsurface models and transient thermal effects to the inversion. Additionally, gravity data will be integrated to refine the 3D crustal structure, and consequently the subsurface temperatures. We use Ireland and Iceland as two case studies to test the methodology at the crustal scale, for full island and local scale approaches.

## AS25-0866

# Unraveling the Upper Mantle Heterogeneities of the South African Cratonic Region Using Seismic and Gravity Data

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Seismic tomography provides critical insights into the Earth's interior, yet seismic velocity perturbations are largely influenced by temperature variations. Integrating seismic data with gravity anomalies enables a more comprehensive understanding by incorporating compositional variations in the upper mantle of Precambrian cratons. The South African cratonic region, encompassing the Kaapvaal and Zimbabwe cratons, exhibits significant upper mantle heterogeneity in both temperature and composition.

To unravel these variations and their corresponding density anomalies, we employ an integrative approach that jointly interprets seismic tomography and gravity data. Our method combines a global surface seismic tomography model with an embedded regional model, derived from teleseismic S-body wave inversion using data from the Southern African Seismic Experiment. Initially, we invert the seismic model for temperature, assuming a refertilized upper mantle composition. Through an iterative process, we adjust both temperature and composition by progressively increasing iron depletion to match the residual density derived from joint inversion of residual gravity and topography data. The GOCE gravity gradients are also incorporated to increase the robustness of the method.

Our results reveal that the most depleted lithosphere is found in the Southeastern Terrane of the Kaapvaal Craton and the central region of the Zimbabwe Craton at depths shallower than 100 km. These areas exhibit temperatures exceeding 150 °C relative to a refertilized lithosphere, providing key insights into the thermochemical evolution of the South African cratonic region.

## AS25-0981

# Deciphering Crustal Complexity: Surface Wave Dispersion and Receiver Function Constraints on Thermal and Compositional Variability

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Understanding the thermal and compositional properties of the crust is challenging due to the lack of direct measurements. A useful way to study these properties is by combining different seismic observations with thermodynamical modeling.

In this study, we use data from a dense seismic network in the greater Alpine region. We compute interstation dispersion curves from ambient noise cross-correlation between 724 broadband stations and receiver functions at 402 stations for teleseismic events of Mw > 5.5 between 25 and 95 degrees of epicentral distance. This allows us to map Moho depth, average shear-wave velocity (Vs) and Vp/Vs ratio of the crust

By using thermodynamical modeling, we interpret the seismic observables in terms of lateral variations in composition (silica content) and thermal properties (average linear thermal gradients) of the crust. We also account for the effects of porosity, fractures, and thick sedimentary layers for the interpretation. Our results indicate that linear thermal gradients exhibit a predominant north-south variation across the study area, with the most significant differences occurring between the cold, silica-rich Variscan crust and the hot, silica-poor Apenninic crust.

## AS25-1042

# Assessing crustal heterogeneities and thermal processes in the Southern Apennines through 3D thermo-rheological modeling

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Southern Italy is a tectonically active region of great geodynamic significance, where seismic hazard assessment and resource management are key challenges. The area is shaped by plate convergence, lithosphere delamination, and active fault systems, leading to a highly heterogeneous crust. Variations in composition, temperature, and fluid content control the mechanical behavior of the crust and upper mantle, making it essential to understand these thermochemical heterogeneities. This study integrates high-resolution seismic tomography with petrophysical constraints and geological-structural information to develop a 3D crustal model of the Southern Apennines at 5 × 5 × 1 km resolution. Our methodology ensures model robustness through multi-scale validation using borehole data, 2D sections, and 3D potential field surfaces. A significant improvement is the construction of continuous 3D surfaces, overcoming limitations of localized 2D interpretations in this geologically complex region. By integrating geophysical and geological-structural data, we developed a model that enables advanced 3D thermo-rheological simulations, providing insights into how geometry and thermal properties influence the regional thermal budget and surface heat flow. Results highlight the role of fluids and lithospheric heterogeneities in heat transport, affecting thermal evolution and deformation. These findings have direct implications for geodynamics, seismic hazard assessment, and geothermal resource exploration, providing a comprehensive framework for understanding deep crustal processes and their surface effects. This work is supported by the research project TRHAM- "Relation between 3D Thermo-Rheological model and seismic HAzard for the risk Mitigation in urban areas of Southern Italy" funded by the European Union—Next Generation EU, PRIN 2022 PNRR-P202299L2C.

## AS25-1265

# An integrative model of the lithosphere of Northeastern Eurasia

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Understanding the thermal and compositional structure of the lithosphere is essential to gain insights into its evolution, as it plays a crucial role in shaping tectonic processes, continental stability, and mantle dynamics. Although several geophysical and petrological studies have been conducted to investigate the lithospheric structures in parts of Northeastern Eurasia, several important issues remain unresolved. In particular, the area east of the Verkhoyansk Range remains one of the least explored areas in the world, having a very limited seismic data coverage. In this study, we determine variations in density, temperature, and composition of the lithosphere and underlying upper mantle of this large area, by applying an integrative technique that jointly interprets seismic tomography and gravity data. We also use the gravity gradients, derived directly from the GOCE mission, to increase the vertical resolution. This approach has provided new insights into the structure of the lithosphere in this region, identifying the origin of its heterogeneities.

## AS25-1397

# A new analysis of the African geothermal potential: new predicted surface heat flow and shallow temperatures from integrated geophysical-petrological inversion

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A detailed understanding of thermal state of the continental lithosphere is a crucial aspect of characterizing the geothermal potential. Surface heat flow values are a direct observation of the temperature distribution in the crust. In contrast to other geophysical data sets, SHF measurements are expensive and can be affected by a number of distorting factors (e.g. advection).

To explore the geothermal potential of the African continent, it is essential to understand the crust and ithosphere structure. To estimate the thermal gradient, it is important to consider factors such as lithospheric thickness (thermally defined), crustal thickness and composition in terms of thermal conductivity and radiogenic heat production. SHF measurements are relatively scarce in Africa, so the use of other geophysical datasets to infer the shallow crustal geotherm in vast portions of Africa is essential.

This study presents thermal models derived from an integrated lithospheric inversion approach, which combines state-of-the-art surface waveform tomography data with additional datasets such as surface heat flow, thermal conductivity, topography, crustal P-wave velocity, and sedimentary thickness obtained from controlled-source seismic surveys. Moreover, we provide and incorporate a a new sedimentary/upper-crustal thermal conductivity model based on the International Heat Flow Commission database.

The results of this study are incorporated into Project InnerSpace's open-source GeoMap platform (https://projectinnerspace.org/), which aims to accelerate the uptake of geothermal energy by improving our knowledge of the subsurface.

## S20 Structure and evolution of Alpine-Mediterranean mountain belts and basins revealed by seismic large-scale passive experiments

### AS25-0115

# Crust and Mantle Structure of the wider Pannonian Basin region: Insights from Receiver Function Analysis

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We present a high-resolution seismic investigation of crustal and mantle discontinuities in the Eastern Alps, Pannonian Basin, Carpathians, and Dinarides using P-to-S and S-to-P receiver function analyses. The Pannonian Basin, characterized by thick sedimentary deposits overlying a crystalline orogenic basement, is surrounded by young orogenic belts with thick crust formed through past subduction and collision events. Previous studies provided incomplete and uncertain mapping of lithospheric discontinuities in this region. Our study utilizes broadband seismic waveforms from over 860 seismological stations -including temporary networks and permanent stations- covering two decades (2002–2023) of data. Quality control and advanced processing techniques allow us to achieve an unprecedented spatial resolution of the lithospheric structures. We introduce new sedimentary thickness, Conrad, Moho, and upper/lower crustal thickness maps, alongside an improved lithospheric model, including the Lithosphere-Asthenosphere Boundary. Moho depths vary significantly, from 20–26 km beneath sedimentary basins to 40–45 km beneath the Eastern Alps and Carpathians. The lithosphere is notably thin (<80 km) in the Pannonian Basin but thickens to ~90–140 km in surrounding orogens, correlating with regional heat flow variations. We further investigate mantle transition zone discontinuities (~410 km and ~660 km depths) to assess thermal and compositional variations, providing insights into mantle dynamics such as subducted slabs and plumes. The Common Conversion Point cross-sections, combined with seismic tomography, reveal structural complexities beneath key regions, including the Vrancea zone and the Eastern Alps-Pannonian Basin transition. These findings refine our understanding of the lithosphere's role in shaping regional geodynamic processes.

## AS25-0178

# Effects of inversion volume size on body-wave tomography – an example from the E. Alps

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Data recorded during large-scale passive experiment AlpArray, series of its complementary projects (e.g., EASI, SWATH-D, PACASE) as well as several other previous small-scale experiments (e.g., ALPASS, BOHEMA, CIFALPS, CPB) allowed to unravel details in structure of the Alpine-Carpathian chain. Tomography images, sometimes controversial, lead to a search of new geodynamic models of the Alpine subductions. Fundamental differences found in images of the E. Alps give rise to several questions: (1) is the E. Alpine slab attached or detached, (2) at which depth the slab resides, (3) in which directions the slab subducts, (4) is the slab of Adriatic or European plate origin, or, of both. All these uncertainties are reflected in models deducing evolution of the Europe-Adriatic plate collision. There are plenty of parameters which affect regional body-wave tomography images and might disturb the real visualization of the E. Alpine slab at shallow depths. In this contribution we test, primarily, effects of crustal models incorporated into the body-wave tomography and size of inversion volume and related parameters as stability of a residual reference base or effects of the out-of-volume heterogeneities. The aim is to get a reliable tomography image of the E. Alpine slab perturbations in the upper ~100 km of the mantle and to answer the basic questions on the subduction beneath the Eastern Alps.

## AS25-0403

# High-resolution 3D imaging of AlpArray teleseismic P-waves using Full Waveform Inversion

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The Alps' tectonics result from interactions between the African, Eurasian, and Iberian plates, along with mantle dynamics. Understanding the crust and upper mantle structures is key to regional geodynamics. Using Full Waveform Inversion (FWI) on teleseismic earthquakes from AlpArray, SWATH-D, and CIFALPS2 networks, we developed the first 3D high-resolution elastic multiparameter FWI models, including P and S wave velocities, and density, from the surface to 700 km depth. The analysis of FWI models at the crustal scale along the Alps captures small-scale anomalies and velocity variations along fault zones, and reveals the subducted European lithosphere beneath the Adriatic. Our results show that Moho depth increases from the southwestern to the northwestern Alps, with a deeper Moho in the Central Alps compared to the Western Alps. In the Eastern Alps, two distinct Moho structures are identified: the Adriatic Moho, which remains flat at 40 km depth, and the European Moho, which extends southward to 60–65 km and subducts along the Penninic Front. At the upper mantle scale, FWI results show continuous subduction of the European slab beneath the Po Basin to 250 km in the Western Alps, with steeper subduction in the southwest and shallower dips in the north. In the Central Alps, the slab reaches 250 km without detaching, though low-velocity anomalies suggest a potential slab gap. In the Eastern Alps, FWI models indicate vertical slab extension beneath the Tauern window, with a low-velocity anomaly hinting at asthenospheric upwelling due to slab retreat.

## AS25-0947

# Toward a New Shear-Wave Velocity Model of Adria Lithosphere from joint inversion of teleseismic and ambient noise surface wave dispersion

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In the intricate tectonic framework of the central Mediterranean, the Adria microplate plays a pivotal role in the evolution of the Alps, Apennines, Dinarides and Hellenides chains. The currently running AdriaArray project has the main goal to improve the imaging resolution of the lithospheric and mantle structure beneath Adria by significantly improving the seismic station coverage in areas where, until now, seismic stations were scarce. Thanks to AdriaArray, new seismic broadband data are now available, giving the opportunity to compute new 3D detailed velocity models of the Mediterranean region, especially of the Dinarides and Albanides-Hellenides system, an area that has been poorly investigated.

We show the analysis of continuous data recorded by about 1100 stations with the objective to compute a new 3D shear wave velocity model. We jointly invert the teleseismic and ambient noise dispersion measurements using the python framework 'Seislib' (Magrini et al., 2022) to obtain the phase and group Rayleigh and Love velocity maps at different periods, from 3s to 150s. To get the final 3D model, we follow a Bayesian approach to convert these maps into a 3D large-scale high resolution model (Magrini et al., 2025). The main strength resides in the amount and quality of new analyzed data that gives the opportunity to improve the resolution of the final images by adding new constraints both on the crustal and mantle structure of Adria. Preliminary results, including surface-wave dispersion curves, and Rayleigh and Love phase/velocity maps of the studied area, will be presented and discussed.

## AS25-0971

# Crustal and lithospheric structures of the Eifel volcanic field

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The Eifel volcanic field in Germany is known for its history of significant eruptions, including the most recent eruption of Laacher See volcano ca. 13000 years ago, which registered a volcanic activity index of 6. Recent studies indicate ongoing movement of magmatic fluids in the crust. For the mantle, various models from plumes to asthenospheric upwelling have been proposed.

To address key questions regarding the large-scale dynamics of the Eifel volcanic field and its current activity, we present a multi-scale tomographic study utilizing data from a local Large-N seismic network, which comprises over 400 stations, together with data from broadband seismic networks in the area. This network enables imaging of the lithosphere-asthenosphere system and local crustal structures.

Our study combines ambient noise recordings with teleseismic earthquake data to obtain broadband phase velocity measurements of surface waves. Constraining both the Vsv component from Rayleigh and the Vsh component from Love wave data allows for the inversion of a 3d shear-wave model that includes isotropic velocities and radial anisotropic features.

The dense station coverage of the Large-N network allows to resolve small-scale crustal features with an extend of only few kilometers, as well as larger trends in LAB thickness. Specifically, we compare the results to the presence of sedimentary basins, the architecture the of Variscan orogen and to the distribution of Cenozoic volcanism in the Eifel area. In addition, we discuss Moho topography as well as the importance of shallow asthenospheric volumes and mantle flow for the intraplate volcanism in the area.

## AS25-1067

# AdriaArray – a Passive Seismic Experiment to Study Structure, Geodynamics and Geohazards of the Adriatic Plate

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The densely populated area around the Adriatic Sea is prone to geohazards including earthquakes, tsunamis, landslides, flooding and volcanic activity as the Adriatic Plate is consumed in a tectonically active belt spanning from Sicily, over the Apennines to the Alps, Dinarides and Hellenides, generating earthquakes up to magnitude 7. To identify drivers of associated plate deformation, the plate boundaries, slabs, properties of active faults and of the stress field have to be determined. AdriaArray, a dense plate-scale regional seismic network (2022–2026), provides data for imaging of the crustal and upper mantle structure and for the analysis of seismic activity. The network consists of 1075 permanent and 440 temporary BB stations from 23 mobile pools. A homogeneous coverage by broadband stations in an area from the Massif Central in the west to the Carpathians in the east, from the Alps in the north to Sicily and the Kefalonia Fault Zone in the south, is achieved. Data recorded by the temporary stations is transmitted in real-time and archived by the EIDA. AdriaArray, the largest passive seismic experiment in Europe so far, is based on cooperation between local network operators, mobile pool providers, field teams, ORFEUS and EPOS, encompassing 64 institutions from 30 countries. We describe the evolution and objectives of the experiment, challenges tackled, we present the maps of the AdriaArray Seismic Network, station properties, coverage, data archiving, contributing institutions and coordination of research by Collaborative Research Groups.

## AS25-1113

# Unraveling the Adriatic Plate Configuration beneath Albania with Teleseismic Full Waveform Inversion

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The eastern margin of the Adriatic plate stands out for its tectonic complexity and geohazard potential in Europe, which are dominated by the northeast-directed subduction and collision of the Adriatic plate with the Eurasian plate beneath the Balkan. Recent studies proposed different conceptional models including horizontal and vertical slab tearing beneath this area. Despite the importance of this region, seismic imaging is still insufficient to resolve these fundamental geodynamic processes.

To answer these important geodynamic questions, we employ the advanced wavefield-injection teleseismic full waveform inversion (TELEFWI) to image the seismic velocity structure beneath Albania. The TELEFWI explores waveform recordings from 9 high-quality teleseismic earthquakes recorded by 50 broadband stations from the ANTICS array (Albanian Tectonics of Continental Subduction). TELEFWI reveals detailed structures from the crust down to 220 km in depth, with spatial resolution up to 5–8 km in the crust and uppermost mantle.

This model displays a strong eastward-dipping high-velocity anomaly from about 30 km depth below the coast down to 80 km to the east, which we suggest being the expression of the subducting Adriatic plate. The interface of the subducting plate from this study correlates very well with the receiver functions migration results (Tilmann et al., this meeting). Strong low-velocity anomalies in the upper crust are also observed beneath the basins, probably representing the thick sediment layer.

In summary, this study provides a high-resolution velocity model for the first time based on teleseismic full waveform inversion and sheds light on the Adriatic plate configuration beneath its eastern margin.

## AS25-1193

# Paleomagnetic rotations and microplate/terrane dispersal during back-arc basin opening: the Greater Iberia fragmentation

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The Oligocene-to-present fragmentation and dispersal of the Alpine chain through the spreading of diachronous back-arc basins (Liguro-Provencal, 30–15 Ma; Tyrrhenian Sea, 10–2 Ma) induced the migration of microplates and terranes. The Corsica-Sardinia microplate rotated counterclockwise (CCW) by 50° during Oligo-Miocene and the Calabro-Peloritan, Kabylies and Alboran, known all together as AlKaPeCa, presently form enigmatic basement terranes stacked over the sedimentary successions of the Apennines-Maghrebides. Here we show the synthesis of paleomagnetic vertical-axis rotations from the sedimentary cover of the Calabrian and Peloritan terranes (Meso-Cenozoic), SW Sardinia (mid-late Eocene), and a re-evaluation of previous paleomagnetic results.

Data indicate that South Sardinia, Peloritan and Calabrian blocks belonged to the "Greater Iberia plate" before mid-Oligocene (<30 Ma) dispersal, as they all show its characteristic paleomagnetic fingerprint (middle Cretaceous 30°-40° CCW rotation). Rifting of the Liguro-Provencal between 30 and 21 Ma induced 30° CCW rotation of both South Sardinia and Calabria blocks, whereas the Peloritan block, located further south, was passively drifted SE ward at the non-rotation apex of a Paleo Appennine-Maghrebides orogenic salient. South Sardinia plus the adjacent Calabrian block and North Sardinia-Corsica blocks assembled in the early Miocene and rotated 60° CCW between 21 and 15 Ma. After 10 Ma the Calabrian block detached from south Sardinia following the opening of the Tyrrhenian Sea and rotated 20° clockwise (CW), at the apex of a Neo Appennine-Maghrebides Arc. On the other hand, the Peloritan terrane rotated 130° CW on top of the Sicilian Maghrebides, along the southern limb of the orogenic salient.

## AS25-1250

# Seismo-tectonic structure of Albania using an AI-based earthquake detection workflow and local earthquake tomography

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Despite being one of the most seismically active countries of Europe, Albania's seismicity and velocity structure remain poorly constrained. The country is located within the active continental collision between the Adriatic microplate and Eurasia, and in 2019 hosted a damaging Mw=6.4 earthquake that caused 51 fatalities. Here we produce a detailed catalogue of seismicity and characterise the seismo-tectonic structure of the region based on data collected by a recent large-N seismic deployment (382 stations, spacing 6 km).

Our semi-automatic workflow incorporates the detection and association of phases using an AI-based picker and associator, inversion of a local velocity model for both P- and S-phases, and relocation of the entire catalogue using our newly derived velocity model. The assembled catalogue contains 18k events, with local magnitudes between -1 and 4.5. The seismicity is concentrated in clusters and along major known structures, with hypocentral depths mostly in the range 5–25 km. Two particular clusters are noteworthy, with up to 800 events per day and focal mechanisms showing oblique-normal faulting consistent with the kinematics of nearby structures. Average noise amplitudes (used as proxy for station quality) and station correction terms (derived from the velocity model inversion) show a strong dependency with first-order geological features such as large Neogene-Quaternary basins and compact Mesozoic-Tertiary deposits. Finally, we compare our results to a newly developed 3D S-wave model based on teleseismic FWI. Our results help to better understand the seismogenic processes occurring in this region, particularly in relation to the active continental collision and its associated seismic risk.

## AS25-1262

# Reevaluating local and regional seismicity in the Carpathian Basin using multiple event location algorithms and ground truth data

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The Hungarian National Seismological Bulletin has undergone substantial improvements through advancements in velocity models, seismic network coverage, and localization methodologies. A key challenge in regional seismology is differentiating tectonic earthquakes from anthropogenic sources, as many recorded events stem from mining activity, potentially biasing geological interpretations. The Kövesligethy Radó Seismological Observatory's digital dataset, maintained since 1995, enables a comprehensive reassessment of seismicity in the Pannonian Basin.

By 2018, hypocenter parameters for 5,735 seismic events were refined using the 3D RSTT velocity model, demonstrating its efficacy in regional event location. Since then, the dataset has been extended to 12,313 events, incorporating the highest-quality initial parameters.

This study integrates the BayesLoc algorithm (1995–2023) for regional seismicity assessment and employs the double-difference method for precise relocation of event clusters (e.g., Somogyszob, Szarvas, Móri-árok). Event classification and quality control ensured retention of well-constrained events. GT2 reference events enhanced BayesLoc accuracy, while sensitivity analyses assessed the impact of initial hypocenters, uncertainty parameters, and travel-time corrections.

The results show reduced location uncertainties and improved clustering, particularly for GT2-calibrated event clusters, enabling refined regional seismotectonic interpretations. For seismic clusters, the double-difference algorithm effectively optimized relative event locations. By integrating over 25 years of seismic data into a consistent analytical framework, this study provides the most precise seismicity dataset for the Pannonian Basin, supporting seismic hazard assessment and systematic identification of anthropogenic sources.

## AS25-1306

# Mapping crustal structure from dense receiver function profiles constructed with ANTICS Large-N experiment data

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The Albanide orogen at the Eastern Adriatic plate margin forms the central part of the Dinarides-Hellenides fold-and-thrust belt. It has resulted from eastward directed underthrusting of Adriatic lithosphere. During the late Miocene-Pliocene, the orogen underwent rapid exhumation (3–4 km), suggesting deep-seated thrust systems.

The External Albanides are dominated by thrust faulting with shallow dips, as seen in the highly damaging 2019 MW6.4 Dürres earthquake. In the Internal Albanides, normal faulting mechanisms prevail. Strike-slip and oblique mechanisms occur in the transition between both regimes.

We report preliminary results from the ANTICS experiment in central and southern Albania. Following an areal deployment of 332 geophones (4.5 Hz) and 50 broadband stations, we redeployed 214 geophones into dense lines, three perpendicular to the orogen and one along-strike (spacing ~1 km).

Despite the geophones' high corner frequency, converted phases can be identified in common conversion point stacks. In our southern line, the Adriatic Moho dips from about 30 km depth below the coast, near Vlorë, to about 70 km in the east. A shallower subhorizontal Moho at 35–40 km depth is associated with the overriding Albanides, similar to results from an existing RF line from Northern Greece (Pearce et al 2012), and is also consistent with recent teleseismic FWI results (Gao et al, this meeting). The other profiles also show the Adriatic Moho, though less clear, maybe due to the influence of shallow sediments. We also image a sequence of eastward dipping converters up to >20 km depth, which we interpret as evidence for thrust sheets.

## AS25-1336

# Crustal structure of Rhodopean massif from receiver function analysis

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AdriaArray is a large seismic experiment designed to study the Adriatic Plate and its active margins. In this study, we use data from six seismic stations of the AdriaArray network located in Bulgaria. The stations form a transect across the Rhodopean Massif in an east–west direction. The receiver function technique and petrological modeling were applied to determine the crustal structure along this profile.

A velocity model for each station was derived through the inversion of receiver functions, and the resulting velocity model was subsequently used for petrological modeling. The Moho depth was also determined, varying between 25 and 50 km. The deepest Moho is observed in the western part of the transect, while in the eastern part, the depth is approximately 30 km.

## S21 Integrating Plate Tectonics, Volcanism, and Geodynamics: Insights from the Lithosphere and Underlying Mantle Structure

### AS25-0271

# Ghost plumes hidden beneath Earth's continents—the Dani plume in eastern Oman

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There are rare occurrences on Earth where mantle plumes intersect with continents, resulting in surface volcanism. Unlike their more common counterparts in oceanic lithosphere, where the ascent of melts is facilitated by a thinner lithosphere, identifying continental plumes is challenging. Surface volcanism, traditionally a key indicator of mantle plumes, may play a diminished role in continental interiors, where a thicker lithosphere restricts plume ascent and associated decompression melting. Thus, it remains uncertain whether limited continental volcanism implies few sub-continental mantle plumes.

I present interdisciplinary evidence revealing the first clear example of a new, amagmatic "ghost" plume in eastern Oman—the Dani plume. This plume is robustly imaged using P- and S-wave arrival-time residuals from distant earthquakes, recorded by a dense regional seismic network. The presence of the plume is also confirmed by mantle transition zone anomalies, which are overlain by positive present-day residual topography in a region enigmatically uplifted since the late Eocene (~40 Ma). Analyses of kinematic reconstructions demonstrate that asthenospheric flow associated with the Dani plume modified Indian plate motion in the late Eocene, providing a constraint on the likely arrival time of this plume beneath the lithosphere.

These findings imply that other "ghost" plumes likely exist and that there is strong evidence for their existence in the recent geological past. This study suggests that core-mantle boundary heat flux estimates should be revised upward, with implications for thermal and core evolution models.

## AS25-0445

# Delineation of 3D crustal architecture across the Karakoram fault in western Tibet: Integration of seismic velocity and attenuation properties

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The Tibetan Plateau formed due to the convergence of the Indian and Eurasian plates, highlights the Himalayas, Lhasa, and Qiangtang terrane at its western edge. The key geological features of the plateau include the Bangong–Nujiang Suture (BNS), the Indus-Yarlung Suture (IYS), and the Karakoram Fault (KKF). This study is aimed at understanding the crustal architecture of western Tibet, emphasizing upon variations across the KKF, by integrating local earthquake tomography and relocation techniques, shear velocity structure and radial anisotropy obtained from regional earthquake surface wave tomography. The results are complemented with contributions of scattering and intrinsic attenuation parameters using the Multiple Lapse Time Window Analysis across the crust to understand the 3D seismic structure. The local and regional earthquakes data, recorded by an array of 31 broadband seismic sensors operating from 2007–2011, are used to constraint the overall seismotectonic framework to understand the geometry of subducting Indian plate, with emphasis upon the role of crustal flow in the broader India-Asia collision framework. The P-wave velocity is notably low in the regions surrounding the KKF. Significant reductions in velocity observed in the crust beneath the western margin, primarily concentrated beneath the Lhasa Block, while relatively higher velocities are detected in the Himalayan terrane, with the attenuation properties also starkly contrasting across the KKF. Additionally, the observed velocity structures provide evidence of partial melt, and mantle-derived fluids in the crust beneath the Tibetan Plateau and suggest mid-crustal channel flow of lower-velocity crustal material from the plateau toward the Himalayan range.

## AS25-0505

# Is the existing of a weak zone a sign of interlayer decoupling?

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The widespread low velocity zones at the depth of 20 ~ 35 km in the southeastern margin of the Tibetan plateau may have potential decoupling function in the present seismic and tectonic activities by melting from the inner part of the crust.

We analyzed coupling effect by comparing the different depth distribution of the deformation and stress correlation characteristics. This paper calculated the mantle convection stress field in the Sichuan-Yunnan region below the base of the lithosphere using 11–36-order spherical harmonic coefficients in the EGM2008 gravity model. We collected and characterized the focal mechanism solutions of the 4131 earthquakes that have occurred in the Sichuan-Yunnan region since 2000. The current seismogenic layer stress field and stress field before the Lushan earthquake were calculated using damped regional-scale stress inversions.

We analyzed the correlation between the two types of stress field, and explored its relationship with strong earthquakes in different regions. The stress state of the lithosphere and inter-layer coupling interactions are of great significance in seismogenic environment. The coupling effects of deformation at different lithospheric depth and coupling relation between the drag stress generated by mantle convection at the base of the lithosphere and the seismogenic layer stress field in the crust represents the degree of mechanical coupling in the lithosphere.

Result is helpful to understand the coupling effects between the crust and the lithosphere of the Southeastern Tibetan Plateau. Most of the Sichuan-Yunnan region is located in the intermediate zone between coupling and decoupling. The coupling zones are distributed in many blocks.

## AS25-0588

# Polarization anomaly of long-period teleseismic P-waves: Insights into Azimuthal Anisotropy in the Upper Mantle beneath Australia

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Seismic azimuthal anisotropy in the continental upper mantle is key to understanding the Earth's evolutionary history and present dynamics. The Australian continent comprises the cratonic regions in central and western Australia and the eastern province formed by the Phanerozoic orogeny. Several earlier works have primarily inferred anisotropic architecture in the Australian upper mantle from surface-wave tomography (e.g., de Laat et al., 2023) and PKS/SKS (XKS) splitting analyses (e.g., Eakin et al., 2021, 2023; Ba et al., 2023), providing comprehensive discussions on the role of ancient lithospheric tectonics and the present asthenospheric flow.

In this study, we mapped the spatial distribution of the azimuthal anisotropy beneath Australia using polarization anomalies of long-period teleseismic P-waves recorded at permanent and temporary seismic stations. The estimated fast axis orientations across the continent are distinctive for the tectonic provinces. In eastern Phanerozoic Australia and the southern North Australian Craton, fast axes align with the absolute plate motion (APM), consistent with present-day asthenospheric flow. Southeastern Australia, however, indicates large deviations from the APM direction, which may reflect the localized changes of the asthenospheric mantle flow (e.g., Eakin et al., 2023). In cratonic Australia, on the other hand, fast axes generally deviate from APM, suggesting the frozen-in lithospheric anisotropy that reflects the ancient tectonic processes. The resultant fast axes from the P-wave polarization anomaly are not always consistent with the previous XKS results due to the different sensitivities, which may provide alternative insights into seismic anisotropy in the continental upper mantle.

## AS25-0691

# Contrasts in continental and oceanic Subduction beneath the Western Hellenic Trench: Insights from teleseismic Receiver Functions

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The Western Hellenic Trench is a complex tectonic setting where the Cephalonia Transform Fault marks the transition between oceanic subduction in the south and continental subduction in the north. This change in subduction style within the same subduction zone enables us to investigate how the composition of the subducting plate influences its evolution during prograde metamorphism.

In this study, we apply teleseismic receiver function analysis to investigate the contrasting seismic properties of the two subduction regimes. We use two seismic arrays from the MEDUSA broadband network to compute receiver functions, one imaging the oceanic subduction and the other imaging the continental subduction. The receiver functions are further analyzed using Hk-stacking to identify prominent S-wave velocity jumps and, through harmonic decomposition, to characterize isotropic and anisotropic regions of the subducting slab.

By comparing the seismic properties of the continental and oceanic slabs, we aim to identify key differences in slab structure, seismic anisotropy, dehydration, and metamorphism, which, in turn, will provide new insights into how variations in lithology and tectonic setting control the evolution of subducting plates and their distribution of seismicity at depth.

## AS25-0838

# The Lost Lithospheric Roots of the Indian Subcontinent

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Present day Indian subcontinent displays a remarkably thin lithosphere (100–200 km) compared to the global Archean average (250–350 km). While thermal erosion by past mantle plume interactions likely contributed to the removal of lithosphere, it alone cannot fully explain the observed deficit. This study identifies four distinct peaks in India-Eurasia convergence rates over the past 120 million years, correlating with the Kerguelen, Marion, and Reunion magmatic events, plus a minor peak at 50–52 Ma. S-wave seismic tomography data reveals four corresponding high-velocity anomalies within the upper mantle and mantle transition zone, spatially linked to the Indian subcontinent's paleolatitudes during these events. Based on geological and geophysical evidences, we propose that these high-velocity anomalies, represent remnants of Indian deep lithospheric keel, progressively decoupled and removed through delamination, convective dripping, and potentially triggered dripping. Our model suggests the episodic removal of the Indian cratonic root, which likely impacted plate buoyancy and motion and significantly contributed to the dynamic evolution of the Indian plate throughout the Cretaceous-Tertiary.

## AS25-0852

# Integrating in-house depth phase picks to enhance ISC-EHB dataset

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Over the past ten years, the number of depth phase picks reported to the International Seismological Centre (ISC) has steadily decreased. The availability of depth phases is crucial for high quality global earthquake location, as they can be used to constrain the depth of remote earthquakes. To address this decline, analysts at the ISC pick depth phase arrivals for global earthquakes with mb(NEIC) ≥ 4.8 and an NEIC depth of ≥ 28 km. These picks have been used in several ISC products, including the ISC Bulletin, ISC-GEM catalogue and ISC-EHB dataset. The ISC-EHB is a dataset of well recorded earthquakes with a prime magnitude > 3.75. We illustrate noteworthy features in several regions, including some of those presented in Engdahl et al. (2020)**.** This dataset can be used for regional and global seismicity and tomographic studies, especially in subduction zones where significant spatial and structural characteristics are observed. The ISC-EHB for 1964 to 2022 and is freely available from the ISC website (isc.ac.uk/isc-ehb), where seismicity maps and cross sections along all subduction zones are shown. The ISC-EHB is updated annually in line with the completion of analysis of the data year in the Reviewed ISC Bulletin.

## AS25-0874

# The southern extent of active Hikurangi subduction: insights from seismicity catalogues

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The Hikurangi subduction zone, which runs along the east coast of Aotearoa New Zealand's North Island, has the potential to host great earthquakes (Mw>8). In the southern Hikurangi margin, the plate boundary undergoes a complex transition across the Marlborough Fault System from oblique subduction to transpression on the Alpine fault. This transition is distributed, and the southern extent of active subduction remains an open question. While some studies suggest that subduction terminates in Cook Strait, the stretch of sea between the two islands of Aotearoa New Zealand, more recent seismicity and geodetic data raise the possibility of an active interface beneath Marlborough in the northern South Island. To study the structure and slip of the southern Hikurangi interface, we review the seismicity in the northern South Island, with a specific focus on the interpretation of earthquake hypocentre locations and focal mechanisms. We compile a catalogue of well-constrained earthquake locations and focal mechanisms from the literature. These hypocentres are compared to the Williams et al. (2013) model of the subduction interface to identify earthquakes that could be associated with active subduction and intra-slab faulting. The data indicates that the Benioff zone and active subduction extends beneath north Canterbury and at least 80 km south of the seafloor expression of the subduction thrust. Rupture of the subduction thrust could pose significant seismic and tsunami hazard in the northeastern South Island.

## AS25-0888

# Radiometric dating and geomagnetic studies on volcanic rocks from Cartagena region (SE Spain)

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In SE Spain two different magmatic phases are recorded during the Cenozoic. The first one, Miocene, is characterized by volcanic rocks with a geochemical signature related to the subduction modifications of their mantle sources. The second phase is younger and is represented by a smaller volume of volcanic rocks. This second phase is characterized by mild alkaline sodic lithologies. Here, we present a field and geochronological analysis of basalts cropping out around Cartagena (SE Spain). We carried out a detailed mapping of vents and lava flows fields, paying special attention to the relationships with the host rocks and the tectonic structures. Furthermore, a geochronological study including both palaeomagnetic analysis and radiometric dating is in progress. We will discuss our results in terms of the regional geodynamic cadre and the potential relationships between volcanisms and active tectonics.

## AS25-0939

# Seismic Evidence for crustal heterogeneity and anisotropy at Yilgarn Craton's southwest margin, Australia

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The southwest margin of Australia records Precambrian cratonization and episodes of Proterozoic to Phanerozoic supercontinent assembly and breakup, offering a rare window into early Earth tectonic processes and their ongoing influence on mineralization and intraplate seismicity in the region. Seismic heterogeneity and anisotropy within the lithosphere preserve crucial records of these debated tectonic processes, but the interpretations of seismic structure in SW Australia have suffered from data limitations. The recent deployment of ~200 broadband seismic stations through the Southwest Australia Network (SWAN: 2020–2023) and WA-Array (2023–2024) provides a unique opportunity to refine our understanding of lithospheric structures in the region. Using ambient noise tomography methods, we inverted for new 3-D isotropic and azimuthally anisotropic Vs models. They present distinct crustal structures associated with the Archean Yilgarn Craton, the Proterozoic age Pinjarra and Albany-Fraser orogens, the Paleozoic to Cenozoic Perth Basin, and the long-lived but seismically inactive Darling Fault. Notably, we identify for the first time a high-velocity (3.8–4.2 km/s) zone in the middle-to-lower crust (> 10 km) along the western edge of the Yilgarn Craton, east of the craton bounding Darling Fault. This anomaly likely reflects underplating processes associated with continental breakup and rifting, overprinting a pre-existing weak zone formed and/or reworked in the Archean to Proterozoic. Our results highlight significant structural heterogeneity in the deep crust across the Yilgarn Craton's western margin, suggesting that the tectonomagmatic processes shaping craton margins can extend deeper and affect broader regions of continental crust than what is evident at the surface.

## AS25-0943

# Multifrequency P-Wave Tomography: A 3D Model of the European Mantle

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Seismic tomography has advanced our understanding of the European mantle, revealing the sources of Cenozoic rifting and volcanism in Central-Western Europe and subduction dynamics in the Mediterranean. However, current models face limitations: high-resolution studies cover small regions, while broader models lack the detail to resolve finer structures, especially at depth.

This study presents EURUS, a 3D P-wave tomography model of the European mantle, built from broadband waveform-based traveltime measurements (2010–2019) and ISC-EHB catalogue data. Our multifrequency approach used 6,407,116 cross-correlation measurements spanning periods from 30 to 2.7 seconds.

EURUS provides high-resolution (~100 km) images of the Euro-Mediterranean mantle to ~1500 km depth. While confirming broad anomalies seen in prior studies, it offers finer details, particularly in the transition zone and uppermost lower mantle.

In the mid-mantle, we identify a slow-velocity column beneath the European Cenozoic Rift System, intersected by a strong high-velocity anomaly in the upper mantle, likely linked to the cold Alpine subducted slab. The extent of the South Mediterranean subduction is still under investigation. These results highlight the potential of body-wave tomography in resolving mantle dynamics, including upwelling and slab behavior.

## AS25-0976

# Multi-discipline platform for earthquake forecasting

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A new initiative on Earthquake Forecasting has been launched, aiming to integrate all possible effective precursors to develop a comprehensive forecasting system. Our plan has been to combine various precursors, including: Physics of Atmosphere and Ionosphere—Atmospheric Chemical Potential (ACP), Latent Heat Concentration (LHC), Total Electron Content (TEC), and jet streams; Geodesy—GPS (Global Positioning System) data and InSAR (Interferometric Synthetic Aperture Radar) measurements; Geophysics—Magnetic anomalies, gravimetric anomalies (GOCE – The Gravity Field and Steady-State Ocean Circulation Explorer); microseismic anomalies; a decrease in the b parameter (b is a parameter that reflects the ratio of weak to strong earthquakes) in the Gutenberg-Richter relation before earthquakes. Radon (Rn) is associated with earthquakes because its concentration in soil, groundwater, and the atmosphere can change before seismic events. We measure radon activity by assessing the effectiveness of its impact on the near-surface atmospheric layer using ACP. ACP calculations were made for 70 earthquakes +M7 in the world for the last 5 years. It includes an anomaly detection feature based on LTSM (Long Short-Term Memory) algorithm (machine learning). It was found out that 91% of the earthquakes analyzed were proceeded by an ACP anomaly. The ACP anomalies prior to Valdivia 1960, Sumatra 2004, Maule 2010 and Iquique 2014 and other earthquakes are calculated. We may assume that deep fluid migration might be a factor of earthquake triggering according to published papers related to geochemical characterization and monitoring of geofluids in tectonophysics and seismicity-oriented researches.

## AS25-1028

# Lithospheric Structure of the Australasian Region Using Full Waveform Inversion of Broadband Data from Permanent Networks and AusArray Deployment

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Lithospheric structure is fundamental to understanding Earth's dynamic processes and geological systems. While existing tomographic models of the Australian lithosphere effectively capture large-scale features, discrepancies persist at finer scales. To address this, we are developing a fully verifiable lithospheric model, ensuring transparency by sharing all datasets and results. In this study, we present initial results from a full waveform inversion tomography model of the Australian lithosphere, resolving structures down to a period of 70 seconds. This model is constructed using seismic data from the Australian National Seismograph Network (ANSN), legacy datasets, and new records from the AusArray 2° × 2° deployment, which has significantly improved coverage in previously unsampled regions. We begin with seismic waveforms from 193 earthquakes (moment magnitude, $M_w$ 6.2–7.5) and subsequently incorporate 165 additional events ($M_w$ >5.0) as the model extends to 70-second periods.

The AusArray project, commenced during the Australian Government's recently completed Exploring for the Future Program, is funded to continue under the new Resourcing Australia's Prosperity initiative. With the continued availability of new data and computational refinements, the model resolution will improve over time. Expanding the inversion to higher frequencies will allow for better constraints using body waves, enhancing tomographic models at periods of 40 seconds and shorter. Our results confirm previously identified large-scale lithospheric structures while revealing new, finer-scale variations across continental Australia, offering deeper insights into the region's geological framework.

## AS25-1112

# 3D lithospheric structure of the Panama microplate from local earthquake tomography: unraveling double subduction in the Isthmus

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The Isthmus of Panama, located at the southern end of Central America, experiences high seismic activity due to its complex tectonic setting, which is characterized by the subduction of both the Caribbean and Nazca plates, posing a potential risk for destructive earthquakes. For the first time, we present a 3D lithospheric P-wave velocity model and Vp/Vs variations for the Panama Microplate using P- and S-wave arrival time data, recorded by stations from three observatories: National Seismological Network of Costa Rica, Institute of Geosciences of the University of Panama, and the Colombian Geological Service. This dataset spans 12 years, from October 2013 to February 2025. We processed and repicked all available waveforms for selected events with a Mw ≥ 2.5, ensuring a high-quality and highly consistent set of P- and S-wave arrival times. With this data set we derived a regional minimum 1D Vp-Vs model along with associated station delays, covering the Panama Microplate. Subsequently, we aim to perform a series of a local earthquake tomography (LET) inversions to obtain a 3D Vp model and Vp/Vs variations using the SIMULPS code. Our preliminary results align well with features documented in previous seismic studies of the region. Moreover, we provide new evidence of an active subduction process along the northern part of the Isthmus of Panama. The new 3D LET, combined of crustal velocity models and Moho topography, will enhance our understanding of subduction zones and crustal geometries in the Isthmus of Panama. This will provide valuable insights for future regional models.

## AS25-1138

# Geologically Current Directions of Motion of 53 Hotspots Estimated from Monte Carlo Inversion

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We previously estimated geologically current rates of hotspot motion of 2 to 4 mm/yr from Monte Carlo inversion of the trend of 56 young tracks of hotspots constrained by the MORVEL set of plate relative angular velocities. To determine the average rate of motion, each realization randomly assigns a motion direction to each hotspot and a globally uniform rate of motion is imposed ranging from 0 to 15 mm/yr. We require the misfit for the solution set to lie in a range that is neither too small nor too large given objectively estimated uncertainties of observed hotspot trends. From one million realizations, only 21,749 (≈2%) gave an acceptable fit. The set of successful solutions also contains information about what directions of hotspot motion produce misfits to the observed trends that are significantly better than those obtained assuming fixed hotspots. For each hotspot we generate a Rose diagram showing the distribution of the direction of motion for the successful realizations.

We test the directions of motion for each hotspot using the Rayleigh test of uniformity. Six of the 53 hotspots had a value of $p > 0.05$, which is not significantly different from a uniform distribution. The other 47 hotspots tend to move perpendicular to the plate-motion direction. Hotspots with directions of motion that deviate from plate-motion perpendicular occur on slow-moving plates or have relatively large values of p or are situated on a plate boundary producing trends on two plates. Implications will be discussed.

## AS25-1144

# Volcanism and long-term seismicity controlled by plume-induced plate thinning

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Mantle plumes, the hot upwellings from the Earth's core-mantle boundary, are thought to trigger surface uplift and the emplacement of large igneous provinces (LIPs). Magmatic centres of many LIPs are scattered over thousands of kilometres. This has been attributed to lateral flow of plume material into thin-lithosphere areas, but evidence for such flow is scarce. Here, we use new seismic data and new methods of seismic thermography to map previously unknown plate-thickness variations in the Britain-Ireland part of the North Atlantic Igneous Province, linked to the Iceland Plume. The locations of the ~60 Myr old uplift and magmatism are systematically where the lithosphere is anomalously thin at present. The dramatic correlation indicates that the hot Iceland Plume material reached this region and eroded its lithosphere, with the thin lithosphere, hot asthenosphere and its decompression melting causing the uplift and magmatism. We demonstrate, further, that the unevenly distributed current intraplate seismicity in Britain and Ireland is also localised in the thin-lithosphere areas and along lithosphere-thickness contrasts. The deep-mantle plume has created not only a pattern of thin-lithosphere areas and scattered magmatic centres but, also, lasting mechanical heterogeneity of the lithosphere that controls long-term distributions of deformation, earthquakes and seismic hazard.

## AS25-1440

# Large igneous provinces and the importance of past rifting episodes

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Past episodes of rifting and plate thinning are often thought to develop into weak spots where magmatism and deformation can concentrate during subsequent rifting and large igneous province development. Yet, the Turkana Depression in East Africa—which was site of a failed rift system—surprisingly exhibits relatively minor magmatism compared to the Ethiopian Plateau to the north, despite being exposed to similarly hot plume mantle rising from below. We use joint inversion of surface-wave and receiver function data to constrain crustal and upper-mantle seismic structure below the Depression. Evidence for lower-crustal intrusions, ubiquitous below the flood-basalt-capped Ethiopian Plateau to the north, is comparatively lacking, particularly below the Depression's failed Anza rift terranes which ongoing East African rifting is circumnavigating, not exploiting. The mantle lithosphere below the Depression has also retained its cool, fast wave-speed `lid' character, in contrast to the Ethiopian Plateau. These results indicate that instead of weakening the lithosphere, failed rifting accompanied by low-degree melting can deplete the lithosphere of volatiles, rendering it dry and refractory, and ultimately reducing its potential for further melting and deformation.

## S22 The main lithospheric discontinuities, Imaged by Seismic Anisotropy and Integrated Studies, and their influence on the Earth's tectonics

### AS25-0023

# Imaging of crust and lithospheric mantle of Pan-African mobile belt, Lützow-Holm Complex, Antarctica, derived from active and passive seismic experiments

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The Lützow-Holm Complex (LHC) in East Antarctica experienced regional metamorphism as a part of Pan-African orogens. Active seismic surveys for elucidating structure of crust and lithospheric mantle were conducted on the continental ice sheet of LHC by SEAL (Structure and Evolution of the Antarctic Lithosphere) project in 2000–2002. Detailed velocity structures were derived through refraction and wide-angle reflection methods using large-energy explosive sources (Yoshii, 2004). The architecture of seismic reflective layers around the Moho was clearly imaged in terms of conversion tectonics when forming the LHC (Yamashita, 2006). The obtained lithospheric structures were integrated with surface geology and geophysical dataset to evaluate anisotropic patterns that contain rock deformation and flow mechanism associate with past plate motion. This integration also revealed deep-seated tectonic heterogeneities within lithosphere of LHC relating to formation and breakup of the Gondwanaland (Kanao, Tectonophysics, 2011). Furthermore, density models were obtained based on gravity measurements along the survey lines on the same plateau (Toda, 2014). In coastal outcrops in LHC, shallow reflection surveys were also conducted in 2008 and 2011 to reveal geological structure and upper crustal boundaries. It is also planned in future by dense stations using portable high-energy active sources (PASS; Tsuji, 2021). In this presentation, seismic structure with discontinuities of the crust and lithospheric mantle derived from active and passive sources are demonstrated involving tectonic evolution of LHC, where is crucial location for studying amalgamation and breakup of the supercontinent that once spanned over southern hemisphere in Earth's history (Brown, Gondwana Res., 2001).

## AS25-0089

# Seismological constraint of the fossil suture zone in the eastern Central Asian Orogenic Belt

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The eastern Central Asian Orogenic Belt (CAOB), shaped by the closure of the Paleo-Asian Ocean (PAO), features alternating blocks and suture zones, making it an ideal area for studying fossil suture zones. It includes the Solonker suture and the Heihe-Hegenshan suture (HHS), where tectonic controversies of these two suture zones have hindered reconstructions of the region's tectonic evolution. In this study, we deployed a dense short-period array across the Solonker suture and the HHS in the eastern CAOB, and we utilized the passive-source receiver function technique to image high-resolution crustal structures. Our imagings reveal remnants of fossil subducted slabs from both southward and northward subduction along the Solonker suture, and a Moho offset related to the northward fossil subducted slabs in the HHS. These findings, combined with geological evidence, suggest that the Solonker suture marks the closure of the main PAO's basin, while the HHS is related to the closure of a branch ocean basin. Therefore, the identification of fossil suture zones underscores the effectiveness of dense short-period seismic arrays in providing cost-effective constrains on "frozen-in" crustal information, essential for understanding tectonic evolution.

## AS25-0099

# Crustal architecture of the central and western Superior craton, Canada: insights from receiver function analysis

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The western Superior craton preserves >3 billion years of geological history, making it an exceptional natural laboratory to explore the evolution of the Earth's ancient crust. Despite its geological importance, our understanding of the crustal structure in this region has remained relatively sparse, mainly due to limited data sets and basic analysis methods used in past studies. Here we use P-wave receiver functions (PRF) derived from earthquake data recorded at 16 Canadian seismograph stations over the period 2003–2023; this long-term dataset (5–20 years per station) permits a more detailed analysis of crustal architecture than prior studies. H-k stacking is employed to obtain initial estimations of the crustal thickness and the Vp/Vs ratio of the crust. Moho depth varies from ~33 km to ~45 km through most of the province and bulk crustal composition ranges from felsic to intermediate. To infer detailed crustal shear-wave velocity, we perform a joint inversion of the PRF with Rayleigh wave phase-velocity dispersion data within several back-azimuthal bins. This approach highlights structural variations for different directions around each station, providing valuable insights into the 3D crustal architecture. We also conduct harmonic decomposition for stations with a broad azimuthal coverage to investigate possible sources of anisotropy. Significant variations in crustal characteristics are observed across the region, from relatively simple structure and a sharp Moho to a layered crust and more gradual crust-mantle transition. We explore the variability in crustal structure and anisotropy in the context of the assembly and tectonic evolution of the Superior craton.

## AS25-0134

# Crustal imaging of the Archean cratons

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A craton is the old and stable part of the continent which has remained intact throughout a lot of cycles of crustal formation and deformation since the Precambrian times. Studying their structure can build the understanding of the earth's Precambrian crust and its evolution which is still a matter of debate. Resolving this requires better geophysical imaging of the earth's crust and comparing the different Precambrian cratons together. Receiver function (RF) is a well-known seismological method for finding shear velocity-depth structure beneath a seismic station. Non-linearity and non-uniqueness are two basic problems in RF inversion. Joint inversion of different data is often used in many scientific problems to minimise these effects. Here, joint inversion of RF and surface wave group velocity dispersion data have been used to address these problems. In this study we have studied the global Archean cratons using the widest range of stations, a total of 497, and found out the variation in the crustal depth using two methods. First, we used the H-κ stacking method to get the average crustal thickness and the average Vp/Vs ratio for the stations. Second, using this Vp/Vs value in the initial model we jointly inverted the RF data with the Rayleigh Wave group velocity dispersion data. This study also presents the trends shown by the crustal thickness and Vp/Vs with the ages of the cratons.

## AS25-0157

# A novel method for high-resolution crustal structure detection: Pn-wave receiver function

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The receiver function method has become the most widely used technique for imaging crustal and upper mantle structures due to its low observational cost and high signal-to-noise ratio in deep seismic detection. However, its resolution remains significantly lower than that of the deep seismic reflection method, typically providing only fundamental crustal structure features. To address these limitations in natural earthquake-based crustal imaging, we present an innovative Pn-wave receiver function methodology based on three theoretical foundations: (1) Critical-angle refraction of Pn-waves along the Moho interface maintains consistent propagation angles during extended mantle paths, satisfying plane wave approximation criteria. (2) Pn waveforms recorded at epicentral distances of 5°–15° remain uncontaminated by other seismic phases. (3) Polarization-based particle motion analysis enables robust separation of Pn waves and converted S-phases, eliminating conventional near-vertical incidence requirements. Theoretical modeling and raw seismic data analysis demonstrate three transformative advantages of this methodology: (1) Utilizing propagation paths shorter than teleseismic distances preserves rich high-frequency components (20–30 Hz). The resulting receiver functions achieve 1–3 km lateral and 0.2 km vertical resolution above 40 km depth, comparable to deep seismic reflection profiling. (2) Larger Pn-wave incidence angles relative to teleseismic P-waves amplify converted wave amplitudes, enabling detection of intracrustal interfaces with subtle velocity contrasts. (3) Unlike the teleseismic receiver function, the multiple waves show weak amplitudes in Pn-wave receiver function. Consequently, the new method avoids interference of multiple waves on other converted waves and eliminates artificial interface artifacts common in conventional receiver function imaging.

## AS25-0182

# Moho depth form P-receiver functions in the northern promontory of the AdriaArray

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We present the Moho depths in the northern promontory of the AdriaArray experiment derived from P-to-S receiver functions calculated from broad-band P-coda waveforms from teleseismic events recorded at temporary and permanent stations operated in a region within 10–23º E and 47.5–52º N during last two decades. By the Zhu and Kanamori (2000) and the Ps time delay methods with different crustal models, we process data collected from currently active AdriaArray Seismic Network (since 2022), PACASE experiment (2019–2022), AlpArray Seismic Network (2015–2019) and its complementary experiment AlpArray-EASI (2014–2015), as well as from previous passive seismic experiments in the region – BOHEMA I-IV (2001–2014), PASSEQ (2006–2008) and EgerRift (2007–2013).

We aim at upgrading the current knowledge of the crust in the broader surroundings of the European Alps (Michailos et al., 2023), the Bohemian Massif (Kvapil et al., 2021), the Pannonian Basin (Kalmar et al., 2019), and the Carpathians. Differences between the Moho depths from individual methods could locally exceed 5 km, which may reflect various sensitivities of individual methods to the local complex structure. An extended amount of data and regionally combined evaluation provide a homogeneous estimate of the Moho depths, particularly for the usage in deep Earth studies, e.g., in applying crustal corrections in the upper mantle tomography of Europe.

## AS25-0184

# Towards a self-consistent anisotropic model of the upper mantle based on shear-wave splitting and P-relative residual variations

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[3] *https://orfeus.readthedocs.io/en/latest/adria_array_main.html, AdriArray, Europe, Other*

Generally used averages of time delay and polarization azimuth pairs evaluated from shear wave splitting lead to simplified anisotropic models of the upper mantle, which are often interpreted by the present-day flow in the sub-lithospheric mantle. We propose a new method directly exploiting variations in width of elliptical particle motion (PM) of interfering split shear waves. This method allows measuring anisotropic characteristics for a larger amount of waveforms and also improves azimuthal coverage in a region. An advantage of the method is that the width of the PM is invariant of potential mis-orientation of sensors. We plot the normalized width of the PM, set as a ratio of lengths of the minor to major axes, in dependence on back-azimuths and incidence angles. Variations of the PM width with back-azimuth exhibit four extremes with different amplitudes which reflect wave propagation through the anisotropic upper mantle. We integrate these results with variations of relative P-wave residuals to develop a robust, 3D self-consistent anisotropic model. We test the PM method on a set of SKS waveforms recorded at a subset of stations included in several recent or running passive seismic experiments (EASI, AlpArray, PACASE, AdriaArray). The stations form a band of about 200 km broad running from the western Bohemian Massif through the Eastern Alps to the Adriatic Sea. The combined analysis of the anisotropic parameters of the P and shear waves reveals distinct regional variations delineating complex, domain-like 3D anisotropic structures of the mantle lithosphere related to major tectonic features.

## AS25-0326

# Receiver Function and potential field studies to improve the understanding of the Alpine-Tethys suture in the Western Carpathians

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The Alpine-Tethys suture in the Western Carpathians is represented on the surface by a ~600 km long but narrow, sub-vertical unit called the Pieniny Klippen Belt (PKB). PKB is composed of shallow marine limestone klippens in the matrix of flysch deposits with "exotic" clasts. The above-mentioned features led to the theory of the presence of a Briançonnais-like island, the Czorsztyn ridge, in the middle of the Alpine-Tethys Ocean.

The current passive seismic experiment is aimed at testing this hypothesis. Eighteen seismic stations have been deployed across a north-south profile from Krakow to northern Hungary. Data from this profile, in addition to nine existing stations, has been processed using receiver functions to produce so-called Common Conversion Point (CCP) images, that reveal seismic interfaces in the subsurface.

The CCP images show distinct Moho at ~30 km depth along with a Moho step beneath the PKB. No distinct crustal block can be observed underneath the Tatra nappe where the Czorsztyn basement was theorized to have been subducted to. The images also suggest that the basement is involved in the compressional deformation of the foreland that so far has been considered a thin-skinned fold-and-thrust belt. Further studies, including receiver function inversion, will give more insight into the nature of the suture.

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## AS25-0331

# Seismic azimuthal anisotropy in upper mantle beneath Bhutan Himalayas from the shear wave splitting using SKS, SKKS phases

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This study presents a detailed seismic anisotropic splitting signatures beneath Bhutan by analyzing core-refracted SKS and SKKS phases to unravel mantle deformation and its role in the geodynamical evolution of the eastern Himalayas. Shear wave splitting parameters, including fast polarization direction (φ) and delay time (δt), were unraveled from high-quality SKS and SKKS (XKS) waveforms (≥2.5 signal-to-noise ratio) recorded by 45 seismic stations. The dataset consists of earthquakes of magnitude ≥5.5, with SKS phases from epicentral distances of 84°–145° and SKKS phases from 84°–180°. The observed SW-NE to WSW-ENE fast polarization directions propose that anisotropy results from both the Indian plate motion and preserved lithospheric deformation due to the India-Eurasia plate collision. An increasing delay time trend in western and central Bhutan is linked to Indian plate subduction, while an abrupt decline in splitting and null measurements beyond this region indicates vertical or near-vertical bending of the subducting slab, preventing XKS phases from scanning the anisotropic properties. Additionally, corner flow from the Eastern Himalayan Syntaxis may interfere with splitting signals due to complex anisotropic layering. The discrepancy in splitting measurements between western and eastern Bhutan is attributed to variations in the northward extent of the Indian plate. A comparative analysis of fast polarization directions, absolute plate motion, and GPS data suggests incoherent deformation, indicative of crust-mantle decoupling. These findings provide new insights into the deformation processes beneath the Bhutan Himalaya and their implications for regional geodynamics.

**Keywords**

Seismic anisotropy, Bhutan, Himalayas, SKS/SKKS phases, Eastern Himalayan Syntaxis

## AS25-0333

# Moho and Lithosphere-Asthenosphere Boundary (LAB) below the Sannio-Matese region (Central-Southern Apennines, Italy) from P and S receiver functions

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The structure of the crust-mantle system of the Apennines at the junction zone between the central and southern arcs is poorly known especially due to the lack of deep crustal seismic reflection surveys. This work, part of th MOSAICMO project (MOlise SAnnio Integrated Crustal Model), focuses on the crustal and upper mantle in the Molise-Sannio-Matese region at the junction zone between the Central and Southern Apennines (Italy). The goal is to improve our understanding of the crust-mantle system in this junction zone by identifying the main seismic discontinuities. We calculate 1D seismic velocity models down to ~250 km by a non-linear inversion of both P and S receiver functions, where the velocity model is not known *a priori*. The calculation of RFs is non-automated and a careful selection of data is applied. The models are calculated for stations on two transects, the first located along the axial zone of the Apennine range and the second along the anti-apenninic direction. We show results obtained by applying the P and S receiver function techniques on waveforms from broadband stations of the INGV-RSN network, located along the two transects.

## AS25-0346

# The extent of the Siberian Platform lithosphere beneath the southwestern Laptev Sea Rift System as seen by receiver functions

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The Laptev Sea Rift System is an example for possible initiation of continental breakup. In the North seismicity concentrates on the Gakkel Ridge separating the oceanic parts of the North American and Eurasian plates. Earthquake epicenters are more diffuse on the Laptev Sea Shelf and further inland. The up to 14 km deep rift basins are filled with Upper Cretaceous-Cenozoic sediments. The pre-rift basement is most probably formed by late Paleozoic and late Mesozoic fold belts. The westernmost limit of seismicity is located close to the edge of thick lithosphere of the Siberian Craton. However, the extent of the craton lithosphere towards the Northeast beneath the Laptev Sea is still unclear.

Between 2016 and 2020, temporal networks were installed in the southern Lena Delta and along the western shore of Buor Khaya Bay, within the Russian-German project SIOLA (SeIsmicity and neOtectonics of the LAptev sea region). Receiver functions show a complex crustal structure, that makes it not always easy to identify the Ps converted phase from the Moho discontinuity. However, the majority of stations show clearly early arrivals of the Ps converted phases from the mantle transition zone. Early arrivals of both the P410s and P660s converted phases are very often associated with cratonic-like lithosphere. Therefore, we propose that the Siberian Platform lithosphere extends at least towards the western shore of Buor Khaya Bay, implying that the seismicity along the southwestern boundary of the Laptev Sea Rift System occurs within extended cratonic lithosphere and overlying fold-and-thrust-belt complexes.

## AS25-0355

# 3-D imaging of seismic velocity, anisotropy, and discontinuities in the Australian upper mantle

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Australia is characterized by its unique geological setting with prolonged tectonic history since Archean and has been widely investigated utilizing various seismological approaches in the past decades. In this study, we discuss the seismic velocity structure of the Australian lithosphere and asthenosphere, including the spatial distributions of multiple seismic discontinuities, such as the Mid-Lithospheric Discontinuities (MLDs), Lithosphere-Asthenosphere Boundary (LAB), and X-discontinuities (X-Ds) below LAB. While the background 3-D S-velocity structure is derived from surface wave tomography using multimode Love and Rayleigh waves, the upper-mantle discontinuities are constrained by the joint Bayesian inversions of P-wave receiver functions and the multimode surface-wave dispersion.

Our combined 3-D images of seismic velocity, radial anisotropy, and discontinuities have clarified the seismic velocities and anisotropic properties across each discontinuity. The Australian LAB is generally characterized by increasing radial anisotropy (SH>SV) underneath. In contrast, such anisotropy tends to faint below X-Ds (around 200–300 km depth), suggesting that X-Ds may represent the base of the asthenosphere, where lateral shear flow may control the fast-drifting speed of Australia via basal drag.

Multiple MLDs have been found in the cratonic lithosphere at around 60 and 90 km depths, which are generally characterized by negative velocity jumps in western and southern Australia, except those in northern Australia that indicate positive jumps. Deeper MLDs below 100 km can also be found in the thicker lithosphere beneath central Australia. The cause of MLD is still unknown, but some may represent apparent discontinuities associated with the vertical changes in seismic anisotropy.

## AS25-0361

# Mapping upper mantle discontinuities beneath Australia: a Bayesian approach using P-wave receiver functions and multimode surface waves

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We mapped seismic discontinuities in the Australian upper mantle, including the mid-lithospheric discontinuities (MLDs) above the lithosphere-asthenosphere boundary (LAB) and the X-discontinuities (X-Ds) below LAB. These seismic interfaces provide insights into the continent's evolutionary history. Using the trans-dimensional joint Bayesian inversion with multimode surface waves and P-wave receiver functions from many seismic stations, we reconstructed the radially anisotropic 1-D S-velocity profiles, which provide the local depths of MLDs, LAB, and X-Ds, including the vertical changes of velocity and anisotropy across each interface.

MLDs in cratonic regions are detected at three distinct depths (60–130 km). In the West and South Australian cratons (WAC; NAC), MLDs generally coincide with the negative shear wave speed changes, whereas the North Australian craton (NAC) exhibits positive velocity jumps across MLDs, contrasting earlier S-wave RF studies. These observations highlight the diverse nature of MLDs depending on tectonic provinces.

Bayesian inversion results reveal multiple X-Ds at ~170 km, 220–280 km, and ~310 km depth, below which radial anisotropy generally weakens. The shallowest X-D (~170 km) is found in eastern Australia, potentially marking the base of the high-temperature asthenosphere. The deeper X-Ds (200–300 km) are widespread across the continent, which may reflect the pyroxene phase transitions (Akashi et al., 2009) under the Australian thermal condition (Tesauro et al., 2020). The weakened radial anisotropy below X-Ds supports a transition in the rheological behavior from dislocation to diffusion creep (Karato, 1992), potentially linking some X-Ds to the Lehmann discontinuity (Gaherty & Jordan, 1995).

## AS25-0373

# Use of time residuals to improve Local Earthquake Tomography in the Montello area (Southeastern Alps, Italy)

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A comprehensive model of the Earth's crust is crucial for analyzing observed data and advancing geodynamic and seismological models. In this regard, seismic tomography appears as a powerful tool for investigating the Earth's deep interior, helping us to understand the mechanisms driving tectonic activities. For studies of crustal structure, Local Earthquake Tomography uses the arrival times of P and S seismic waves, which record the local earthquakes; this approach performs a coupled inversion of velocity distributions and source location parameters. In this study, we use the Cat3D software, a tomographic package fully developed at OGS and widely applied in seismic research. Cat3D employs an iterative procedure that computes earthquake locations and estimates P and S wave velocities through traveltime inversion on 3D multi-parametric models. We implement the software by incorporating a time residual analysis after each tomographic step within the iterative process, and, so doing, we improve the accuracy of earthquake depth estimations; it is worth highlighting that the residual correction effects on the earthquake depth, which is the most critical parameter in the location estimations. Specific simulations validate the reliability of our procedure and demonstrate the convergence to the true final model, even when the initial model differs significantly from reality. Our approach is then applied to derive a local 3D velocity structure of the Montello area, located at the outer front of the Southeastern Alps in Italy.

## AS25-0506

# Lithospheric structure and mantle wedge below the Tyrrhenian and Ionian basins (Central Mediterranean) from P and S receiver functions

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We investigate the crustal and upper mantle structure below the Tyrrhenian and Ionian basins using the P and S receiver function technique. These Central Mediterranean basins are part of the Alpine orogen and represent different geological settings, exhibiting distinctive characteristics in terms of age, origin, water depth and crust-mantle structure. The Tyrrhenian basin is in the back-arc, while the Ionian basin lies in a fore-arc setting relative to the Calabrian Arc, where a piece of oceanic lithosphere sinks into the upper mantle, following a slab rollback that occurred in the last 10 Ma.

The broadband seismic stations used in this study (Italian Network) are in Sicily, Ustica Island, the Aeolian Islands, Calabria, and Apulia. Land-based observations are complemented by data from a seismometer at the NEMO-SN1 submarine observatory (Western Ionian Regional Facility of EMSO ERIC).

We present 1D models of Vp, Vs, and Vp/Vs beneath each station, obtained by joint inversion of P and S receiver functions. Our analysis allows us to identify the Moho, as well as the Lithosphere/Asthenosphere Boundary and an underlying low-velocity layer—both of which are mapped here for the first time. The low-velocity layer is interpreted as the mantle wedge above the subducted slab.

## AS25-0627

# Understanding the crustal velocity structure of Western Tibet using Fast Marching Surface Tomography

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The Tibetan Plateau, formed by the collision of the Indian and Eurasian plates, exhibits distinct geological and tectonic features. However, Western Tibet remains less explored compared to the eastern region. Our study investigates surface wave group velocity variations and crustal heterogeneities that may indicate different rock types and fluid content. Using the Fast-Marching method (FMM) algorithm, we analyse the Rayleigh wave group velocity tomography using seismic data from 34 stations within the Y2 Network (2007–2011). Our dataset includes waveforms from 1,588 earthquakes with epicentral distances of 300–1000 km. For each event, we extract dispersion curves to study group velocity variations across multiple periods. Additionally, we rotate seismograms into transverse components to derive Love wave group velocity and implement the FMM algorithm to derive the Love wave group velocity tomography, that is key to understanding the geometry of the subducting Indian Plate. Radial anisotropy delineated from the deviation of the radial and transverse components of the shear velocity offers further insights into the crustal flow within the India-Asia collision framework. Our findings reveal a detailed crustal velocity structure, including a mapped Moho depth of 55–82 km, deepening to 82 km north of the Indus-Yarlung Suture (IYS). The study suggests that the eclogitized Indian lower crust extends to the central Lhasa Block (LB). Furthermore, it sheds light on the dynamics of the Karakoram Fault and the extent of Indian Plate under-thrusting beneath the Tibetan Plateau.

## AS25-0864

# A global and interdisciplinary perspective on variations and dynamics of the lithosphere-asthenosphere boundary

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A debate continues regarding the depth and definition of the lithosphere-asthenosphere boundary (LAB). We compile observations of the LAB from heat flow, seismic tomography, scattered waves, magnetotelluric imaging, and petrology to develop a new synoptic view of the LAB. For oceanic lithosphere, the average LAB deepens from 0–30 km depth beneath ridges to 73–117 km depth beneath the oldest lithosphere. For continents, the average LAB depth is 40–119 km beneath Phanerozoic lithosphere, 122–142 km beneath Proterozoic regions, and 145–180 km beneath Archean cratons. The observed trend of deepening of the LAB with age indicates that temperature plays a first order role in dictating the LAB. However, observations including: 1) age-averaged LAB depths that are often shallow in comparison to the typical paradigm, 2) strong, sharp LAB gradients, and 3) strong seismic and resistivity anomalies in the asthenosphere (from this study and in other works – which will also be discussed) require additional factors. Different mechanisms have been proposed to explain these observations, but none can by themselves explain all observations. Compositional variations and small amounts of hydrated partial melt in the asthenosphere are likely required. Hydrated partial melt would also likely decrease the viscosity of the asthenosphere and affect the depth of the LAB. Interactions of the hydrated melt with solid mantle flow also likely enhance LAB depth variability via upwellings and downwellings, implying a dynamic LAB.

## AS25-0996

# Detecting anisotropy from seismic receiver functions: A review

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The receiver-function (RF) technique relates Ps and Sp scattered waves to flat interfaces beneath a station, usually horizontal. Scattering by dipping interfaces and by layered anisotropy may reflect either active or relict tectonic strain. If the elastic anisotropy exhibits a symmetry axis, RF amplitudes manifest a two-lobed or a four-lobed pattern of scattered-wave polarity and amplitude. These patterns allow RF stacking with harmonic weighting to extract estimates of geologic strain with depth. Dipping interfaces also cause RF back-azimuth variations, coupled with moveouts beyond what anisotropy generates. Interpretations of RF anisotropy include strain localizations within shallow layers, the mid-crust brittle-ductile transition, and sheared basal layers in orogenic regions. The effects of anisotropy on Ps and Sp conversions and on shear-wave birefringence are complementary, with important caveats.

In the shallow mantle, back-azimuth Ps harmonics are commonly observed in subduction zones, sometimes at a single interface, sometimes in a set of dipping layers. Often the back-azimuth variation of Ps amplitude at a slab interface deviates from its known dip. This argues for rock strain from a different flow orientation. Dipping anisotropic interfaces within cratonic lithosphere are a promising indicator of ancient subduction zones and continental sutures. Anisotropic transitions in the 70–150-km depth range, inferred from surface-wave data, may explain the seismic lithosphere-asthenosphere boundary (LAB), but RF body-wave constraints are thusfar fragmentary. Partial melt or grain-boundary sliding could induce the observed wavespeed inversions at the LAB without anisotropic effects. We will review the state of observations and look to the future.

## AS25-1037

# Major Seismic Discontinuities Within the Australian Continent from Receiver Functions of the AusArray Data

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Seismic discontinuities provide critical insights into the structure and evolution of Earth's crust and mantle. In this study, we use receiver functions (RFs) from over 1500 seismic stations across Australia to investigate both shallow and deep discontinuities, leveraging data from the AusArray network alongside permanent and temporary seismic deployments. AusArray, initially funded through the Exploring for the Future program continues with an expanded deployment as part of the Resourcing Australia's Prosperity initiative.

At shallow depths, we estimate sedimentary cover thickness using Ps converted phase delay times, applying an empirical relationship developed from borehole stratigraphy data. This method offers a rapid and cost-effective approach to characterising sedimentary basins, covering a range of geological provinces from Precambrian to present-day.

Beyond the sedimentary layer, we map Moho depth variations across the continent, providing new constraints on crustal structure from the AusArray 2° × 2° network. We further identify lithospheric discontinuities, revealing variations in thermal and compositional properties that define the base of the lithosphere. Within the mantle, we image the 410 km and 660 km discontinuities, which mark phase transitions in olivine. Variations in these boundaries provide insights into temperature, composition, and potential subduction remnants within the mantle transition zone.

This study presents an extensive RF-based analysis of Australian lithospheric and mantle structures using the AusArray network, offering new perspectives on the geodynamic evolution of the continent. By integrating high-density seismic data with advanced RF analysis, we enhance our understanding of Australia's deep Earth structure and its implications for regional and global tectonics.

## AS25-1102

# Moho and intracrustal discontinuity structure variations in the Atlantic from seismic receiver functions using land and OBS data

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The Azores, Canaries and Madeira are three mantle upwelling surface expressions in northern Macaronesia in the Atlantic. While Madeira and the Canaries are located on old oceanic crust as intraplate hotspots (~135 Ma/150–180 Ma, respectively), the Azores result from interaction between a hotspot and the Mid-AtlanticRidge and sit on younger crust (<50 Ma). Mantle upwellings can influence the subsurface discontinuity structure, including shallow crustal contributions, in an area that reaches beyond the locations of the islands into the offshore oceanic subsurface. Therefore, an observation of seismic crust and upper mantle properties in the whole region is key to understanding mantle dynamics and its effect on volcanism.

Offshore seismic measurements are more challenging and globally sparse. From 2021 to 2022 an OBS network was deployed in the oceanic region of northern Macaronesia by the UPFLOW project. With this data it is possible to observe discontinuity variations over a broad area and compare results to landstation data on the islands.

We observe the Moho and intracrustal discontinuities with high resolution as point measurements beneath the stations from P-S receiver functions. Discontinuity strength and depth variations that in some cases can appear over short length-scales could be linked to melt generation and composition changes.

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## AS25-1216

# Study of Seismic Anisotropy in the Intraplate Provinces of South America using the Receiver Function

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Observations of seismic anisotropy provide crucial constraints on dynamic processes in the crust and upper mantle, which are essential for understanding tectonic evolution. Receiver functions show the relative response of the structure beneath the receiver, allowing, for example, the study of anisotropy, particularly for the crust and upper mantle through waves converted at the Crust-Mantle interface, along with methodologies such as Harmonic Decomposition and the Joint Objective Function. Five stations from the Brazilian Seismographic Network and a private USP network with code XC were analyzed, and we obtained a predominantly NS fast direction, with one station showing a SE direction and anisotropy ranging from 0.2 to 0.7. Preliminary results show anisotropy of similar magnitude and a predominant NS direction that may correlate with the boundaries of South American provinces.

## AS25-1257

# Imaging the Lithosphere with Seismic Ambient Noise Autocorrelations in the Martinamor Extensional Dome (Spain)

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Seismic ambient noise autocorrelations provide a powerful tool for imaging the Earth's lithosphere without the need of active sources. In this study, we apply this technique to the Martinamor extensional dome, located south of Salamanca (Spain), to investigate its lithospheric setting. The dome is a Late Variscan syn-collisional extensional system in the Central Iberian Zone, which was part of the northern margin of Gondwana and represents the innermost part of the orogen. The gravitational collapse was accompanied by abundant magmatism, which has drawn attention due to its significance in generating strategic mineral resources. As part of a multi-disciplinary initiative, that aims to construct a high-resolution 3D model of the dome, we deployed a dense network of 60 seismic recorders (spaced 4.5 km apart), that acquired data continuously for 40–45 days. Seismic ambient noise autocorrelations provided us with images of the lithospheric setting of the Martinamor dome. Our results reveal a prominent mid-crustal reflector, the Moho discontinuity, and several reflectors within the lithospheric mantle. These features provide new insights into the deep architecture of the dome and provide the basis to understand its evolution and the ore-controlling processes. The application of seismic interferometry to passive recordings demonstrates the effectiveness of this technique for lithospheric imaging.

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## AS25-1401

# The role and nature of major shallow discontinuities in the upper mantle

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Several decades after the birth of the modern theory of plate tectonics, it is still not entirely clear which physical and chemical processes cause the rheological, geochemical and petrological differences between the lithosphere and the underlying ductile asthenosphere. The mechanisms that cause the outer, brittle lithosphere to move over the deeper, more ductile asthenosphere beneath it are yet to be fully understood. In addition, in recent decades, geophysical methods have discovered discontinuities within the continental lithosphere at roughly similar depths (~100 km). These later mid-lithospheric discontinuities may play a significant role in the detachment and subsidence of the lower part of the continental lithosphere ('delamination'), which in turn can play a significant role in the development of plate tectonics (subduction) and raises the possibility that subduction of oceanic plates can even begin within the interior of the continents. Lithospheric-scale weak zones within the continental lithosphere can also play a role in the 'rejuvenation' of the lithosphere of very thick and old shields, as the very deep roots of the shields can detach along the weak zones and cause significant lithosphere thinning (e.g. East China). Thermo-chemical plume and continental lithosphere interactions can also facilitate these mid-lithospheric discontinuities for geodynamic processes. Geophysical properties of the upper mantle, based on various geochemical models, are presented for these major and tectonically prime discontinuities in the upper mantle.

# Joint Symposia

## J01 Structure and evolution of the lowermost mantle and core from observations and modeling

### AS25-0043

## Constraints on the mantle electrical conductivity from length-of-day changes

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We investigate the impact of the electrical conductivity σ of the Earth's mantle on the downward continuation of the time varying magnetic field from the surface of the core. We document how inverted core surface flows and their associated prediction to the length-of-day changes (LOD) are sensitive to σ. We restrict ourselves to the case where σ is only function of radius, and vary the conductance and the shape of the radial profile in order to document how the conducting mantle delays and smooths the magnetic signal originating from the core. The mantle filter vary with the harmonic degree and the choice of conductivity profile, while the core flow inverse problem further mixes the information carried by single spherical harmonics of the magnetic field. It is thus non trivial to infer the resulting backward delay in LOD predictions. From reanalyses of magnetic field models downward continued through a conducting mantle over the period 1900–2023, we derive various possible LOD contributions from core motions. Their comparison with the geodetic records (lag and correlation) is used to assess how plausible are the considered conductivity profiles. Our results tend to exclude mantle conductances larger than about 10^8 S, when spread over a thick layer. The conductivity values for the 2000 km thick deep mantle, inaccessible by induction studies from above, are then at most about 30 S/m. A highly conducting layer of thickness about 10 km or thinner, for which the lag between observed and predicted LOD would become negligible, cannot be excluded.

## AS25-0123

# Fluid flow and heat transfer in rotating thermal convection and dynamo action with partial stratification in the Earth's core

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This study explores the effects of thermally stable stratification on rotating thermal convection, in an infinite plane layer model, to enhance our understanding of fluid flow and heat transfer in Earth's outer core, with a focus on the polar regions. We investigate the role of stratification in core-mantle interaction, which is crucial for the Earth's dynamo and geomagnetic field generation. Under nonlinear convection, instabilities exhibit characteristics of linear onset modes. As buoyancy forcing increases by 50–100 times, the flow transitions from near-laminar to turbulent, with the damping of small-scale vortical structures and loss of axial symmetry, signaling penetrative convection. Rapid rotation induces small-scale helical flows in the stable layer, essential for maintaining Earth's dipolar magnetic field. Reduced-order modeling reveals coherent flow structures in strongly turbulent supercritical convection. Rotation enhances heat transfer efficiency (up to 30%) within the unstable layer, while stable stratification reduces total heat transfer (up to 25%). However, strong buoyancy forces and rapid rotation can overcome flow suppression, enabling flow penetration necessary for dynamo action. Additionally, we implement and investigate the role of partial stratification near the core-mantle boundary (CMB) using a spherical shell model to further understand heat transfer and dynamo processes in the interior of the Earth's core.

## AS25-0222

# Regionally-triggered geomagnetic reversals

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Systematic studies of numerical dynamo simulations reveal that the transition from dipole-dominated non-reversing fields to models that exhibit reversals occurs when inertial effects become strong enough. However, the inertial force is expected to play a secondary role in the force balance in Earth's outer core. Here we show that reversals in numerical dynamo models with heterogeneous outer boundary heat flux inferred from lower mantle seismic anomalies appear when the amplitude of heat flux heterogeneity is increased. The reversals are triggered at regions of large heat flux in which strong small-scale inertial forces are produced, while elsewhere inertial forces are substantially smaller. When the amplitude of heat flux heterogeneity is further increased so that in some regions sub-adiabatic conditions are reached, regional skin effects suppress small-scale magnetic fields and the tendency to reverse decreases. Our results reconcile the need for inertia for reversals with the theoretical expectation that the inertial force remains secondary in the force balance. Moreover, our results highlight a non-trivial non-monotonic behavior of the geodynamo in response to changes in the amplitude of the core-mantle boundary heat flux heterogeneity.

## AS25-0300

# Ubiquitous low velocity features at the lowermost mantle evidenced from core-reflected shear waves

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Lowermost mantle is characterized by a continent-scaled two massive low seismic velocity structures located beneath the Central Pacific and Africa. Recently, meso-scale low velocity regions distinct from those massive structures have been observed in global tomography models and its mobility and origin were questioned. To revise the global shear velocity patterns in lowermost mantle, we have automatically updated the long-period transverse ScS-S travel time differentials to recent datasets by open-ended shape dynamic time warping. Adopting dynamic time warping enables us to estimate the temporal travel time differentials in the first cycle assessing similarity of the broader window simultaneously. Increasing the dataset, we obtained a ubiquitous delayed ScS-S residual pattern surrounding the paleo-- slabs, suggesting that meso-scale low velocity features are not rare.

## AS25-0360

# Core flow and Earth's rotation on millennial timescales

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A number of recent studies have made use of statistics derived from geodynamo simulations to constrain the flow at the top of the Earth's core. Here we adapt these methods to infer possible core surface flow solutions over the past 9000 years, using a low degree geomagnetic field model, based on archaeomagnetic and sedimentary archives. Despite the low spatial resolution of the field model, we find that the largest scale aspects of the recovered flow agree well with those derived from historical field models. We see approximately bimillennial pulses in westward zonal flow and compare their timing with secular changes in Earth's rotation inferred from ancient astronomical observations. For at least the past 1200 years the modelled flow explains most of the trend in mantle rotation but further back in time the agreement is less clear. We explore various reasons for this, including contributions from unresolved flow and uncertainty in eclipse location.

## AS25-0539

# Effect of complex heat flux patterns at the top of the core on geodynamo simulations

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Heat flux heterogeneities at the core-mantle boundary (CMB) are expected to affect the behaviour of the geodynamo. The reversal frequency of the magnetic dipole has notably been shown to depend on the heat flux pattern at the top of the core in numerical geodynamo models. Heat flux pattern variations driven by mantle convection could thus be causing the changes in the reversal frequency seen in the paleomagnetic record.

Studies with heterogeneous heat flux patterns at the top of the core in numerical models of the geodynamo are usually either focused on large-scale patterns (degree 1 or 2 spherical harmonics) or on the present-day pattern as guessed from seismic tomography. Here, we use heat flux patterns extracted from mantle convection models rotated in the reference frame of the core to study how they affect numerical models of the geodynamo.

We find that geodynamo models with weak zonal flows in the core are very sensitive to heat flux heterogeneities and stay dipolar only when polar cooling of the core is favoured over equatorial cooling. Conversely, geodynamo models with large westward flows are found to be unaffected by complex heat flux heterogeneities. A present-day heat flux pattern is shown to be moderately destabilising, and large amplitudes of heat flux heterogeneities are probably required to significantly destabilise the magnetic dipole. In our models, a multipolar behaviour is associated with an increased equatorial antisymmetry in the zonal flows.

## AS25-0728

# Inner core backtracking by seismic waveform change reversals

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The solid inner core, suspended within the liquid outer core and anchored by gravity, has been inferred to rotate relative to the surface of Earth or change over years to decades based on changes in seismograms from repeating earthquakes and explosions. It has a rich inner structure and influences the pattern of outer core convection and therefore Earth's magnetic field. Here we compile 143 distinct pairs of repeating earthquakes, many within 16 multiplets, built from 121 earthquakes between 1991 and 2023 in the South Sandwich Islands. We analyse their inner-core-penetrating PKIKP waves recorded on the medium-aperture arrays in northern North America. We document that many multiplets exhibit waveforms that change and then revert at later times to match earlier events. The matching waveforms reveal times at which the inner core re-occupies the same position, relative to the mantle, as it did at some time in the past. The pattern of matches, together with previous studies, demonstrates that the inner core gradually super-rotated from 2003 to 2008, and then from 2008 to 2023 sub-rotated two to three times more slowly back through the same path. These matches enable precise and unambiguous tracking of inner core progression and regression. The resolved different rates of forward and backward motion suggest that new models will be necessary for the dynamics between the inner core, outer core and mantle.

## AS25-0776

# Necessary core-mantle boundary heat flux patterns for large latitude of geomagnetic surface intensity minima

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The present-day geomagnetic field at Earth's surface is characterized by an anomalously weak region known as the South Atlantic Anomaly (SAA). Numerical dynamo simulations with an imposed outer boundary heat flux pattern inferred from lowermost mantle seismic anomalies reproduce well the longitude of the SAA, but the latitudes of the modeled surface intensity minima are significantly lower than the observed. Here we explore numerical dynamos with a variety of large-scale synthetic patterns of outer boundary heat flux in order to gain fundamental insight into what patterns may yield large latitudes of surface intensity minima. We find that equatorially anti-symmetric heat flux patterns are required in order to produce large latitudes of surface intensity minima. However, these dynamo models often reverse and their dipole dominance is lost. This trade-off between dipole-dominated models with low latitudes of surface intensity minima as opposed to multipolar models with large latitudes of surface intensity minima is also evident upon increase in the strength of the convection vigor. Snapshots of dynamo models that satisfy the geomagnetic observations in terms of both large latitudes of surface intensity minima as well as large dipolarity exist, but are rare. We speculate that reconciling these two fundamental geomagnetic constraints may be achieved with a larger amplitude of an equatorially anti-symmetric outer boundary heat flux and a more rapidly rotating dynamo model.

## AS25-0861

# Understanding Geomagnetic Field Transitions: A Comparative Analysis of Dipole Moment and PSV Index Dynamics

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Over the years, numerous paleomagnetic studies have provided evidence of multiple geomagnetic polarity reversals and excursions. We utilized some of the most reliable paleomagnetic data-based models such as LSMOD.2, GGFSS70, GGFMB and PADM2M, encompassing different time periods to analyse the field characteristics. The asymmetry in growth and decay of dipole moment and PSV index during different events is examined. A sawtooth pattern of gradual dipole decay followed by rapid recovery during reversals, as proposed by past studies, has been observed in our study on the Matuyama Brunhes reversal. But, in contrast, we observed an opposite behavior of fast-decay and slow-recovery during most of the excursions. Accordingly, the PSV index exhibited a slow growth–fast recovery pattern during the reversal and a fast decay–slow recovery pattern during many excursions, although the PSV index results vary more than the dipole moment results. The same study has been done on the time series of dipole moment and PSV index from each of the models by segmenting the data using different threshold values. Finally, the rate of change (ROC) in the complete time series of Dipole Moment (DM) and PSV index from different models was calculated and compared across different time intervals. The same methods were applied to various numerical dynamo simulations and compared to the data-based findings. Here, we will report the results of this ongoing work.

## AS25-0885

# Stratified regions at the top of the core in thermochemical convection models

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Thermochemical convection in Earth's outer core is driven by the crystallization of the inner core that releases latent heat and light elements. A key question in core dynamics is whether a stable layer exists just below the core-mantle boundary (CMB). Seismic and geomagnetic observations provide conflicting interpretations—seismic anomalies suggest a stable layer, while geomagnetic data indicate radial flow, which a stable layer would suppress. Recent core convection simulations, accounting for CMB heterogeneities, propose locally stable regions (or regional inversion lenses, RILs) rather than a global layer, allowing both stable and unstable regions to coexist. However, a thermochemical model, rather than existing thermal models, is necessary for more accurate predictions of RIL properties.

We consider a suite of numerical thermal, chemical and thermochemical convection models with Ekman number (E=2×10^{-5}), the thermal and chemical flux Rayleigh numbers (Ra_T=3×10^{6}-4×10^8 and Ra_ξ=3×10^{6}-1×10^{10}), and the thermal and chemical Prandtl numbers (Pr_T=1 and Pr_ξ=10). Analysis of purely chemical models shows that the light element may accumulate below CMB if mass flux across the CMB is restricted, leading to locally or globally stable regions. Combined with heterogeneous CMB heat flux, our models predict varying positions and morphologies depending on whether thermal or chemical convection dominates. However, the overall density gradient just below CMB is decided by the thermal field for most of our simulations. In the investigated parameter range, these RILs are O(100 km) thick, with BV frequency O(0.1). The strength and thickness increases with increasing Ra_T, but remains nearly independent of Ra_\xi, if (Ra_T/Pr_T)/(Ra_ξ/Pr_ξ)≥ O(10)$.

## AS25-0960

# Characteristics of the Gauss-Matuyama magnetic field reversal based on a global data compilation

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The geomagnetic field, generated by geodynamic processes in the Earth's outer core, is vital for shielding our environment from solar winds and cosmic radiation. Throughout the history of Earth, there have been non-periodic reversals, in which the polarity switches and the field experiences a substantial decrease. The full global characteristics of geomagnetic field reversals are largely unknown, as only the last one, the Matuyama-Brunhes reversal ca. 780 thousand years ago, has been studied in detail so far. We have compiled a comprehensive global dataset of paleomagnetic records of the second most recent reversal, the Gauss-Matuyama (GM), which occurred ca. 2.58 million years ago. Following up from our past experience with global modelling of the Matuyama-Brunhes reversal by data inversion, our objective in this project is to understand the global characteristics of the GM. This includes: 1) estimating the timing and duration of the GM reversal process; 2) assessing temporal (a)symmetries, e.g. for dipole decay and recovery; 3) understanding the roles of dipole and non-dipole field contributions and spatial characteristics of the reversal. In order to assess these characteristics, paleomagnetic data from 157 volcanic sites, 40 deep-seep sediment records, and 15 shallow deposits have been collected. We checked all data for regional consistency and then built regional and global stacks of virtual axial dipole moment, virtual geomagnetic pole latitude, and paleosecular variation index. Here, we present and discuss our findings about global field properties from these stacks.

## AS25-1360

# Seismic insights into innermost inner core anisotropy and low-velocity torus in the outermost outer core

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Current seismic and correlation wavefield analyses unveil distinct features in two depth domains of the Earth's core: the innermost inner core (IMIC) at the planet's centre and the outermost outer core (OOC) near the core-mantle boundary. For the IMIC, direct PKIKP waves observations, PKIKP multiples (ricochet waves), and coda correlation reveal a ~600–650 km radius, significant anisotropy of ~3–5%, with the fastest propagation aligned with the rotation axis, and the slowest propagation direction ranging from ~45° to ~60° from the Earth's rotation axis. The IMIC's distinct anisotropy relative to the rest of the inner core, its organised fabric, and radial extent may reflect prolonged crystallisation. In the OOC, we detect a low-velocity torus from the coda correlation wavefield, with the velocities reduced by ~2.0% from the surrounding outer core. The torus is inferred to be a global feature in the equatorial latitudes extending several hundred km beneath the core-mantle boundary. However, its latitudinal extent and thickness are less constrained, and further tests are necessary. The OOC's P-wave velocity reduction offers quantitative constraints and suggests dynamic processes linking the inner core with the ceiling of the outer core and the lowermost mantle. The coda-correlation wavefield enhances the resolution of the deep Earth, increasing our understanding and providing critical input for geodynamic modelling.

## AS25-1395

# Influence of the plate motion reference frame on lowermost mantle structure, evolution, and core-mantle boundary heat flow

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Accurate knowledge of the spatial pattern of heat flow across the core-mantle boundary (CMB) and its evolution over geologic eras is of fundamental importance for better understanding the long-term behaviour of the geodynamo. On time scales of tens to hundreds of millions of years, lateral variations of the CMB heat flow are mainly controlled by mantle convection. However, many models of mantle dynamics are still largely qualitative in nature to date. Here, we aim at generating robust predictions of lower mantle thermal evolution based on compressible high-resolution mantle circulation models (MCM) with 410 million years of plate motion history. This is roughly equivalent to two mantle overturns. The time span of geologically-informed structure above the CMB will thus cover at least one full superchron cycle. To estimate uncertainties in lower mantle evolution, we will employ systematic variations of model parameters with a focus on the underlying absolute plate motion reference frame. Appraisal of the MCMs will be done through geodynamic-tomographic model comparisons and by predicting seismic data for direct comparison to Earth observations. Long-period normal mode data are particularly suited in this context, as they provide global constraints, and it has been shown that splitting functions show high sensitivity to variations in absolute reference frame. The estimates of mantle thermal evolution and CMB heat flux that we aim for in this project can in future be linked to geodynamo models and thus be used to compute synthetic time-series of Earth's magnetic field behaviour.

## AS25-1444

# Attenuation of the lower mantle from measurements of differential body waves

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The lowermost mantle is one of the most heterogeneous and enigmatic regions in Earth. Over the past decades, elastic tomography models of the mantle have been numerous and are increasingly detailed. Whilst upper mantle attenuation is relatively well understood from body and surface waves, there have been few lower mantle attenuation studies using body waves or normal modes. Our aim is to measure the attenuation within and outside the two antipodal Large Low Velocity Provinces (LLVPs), since this will provide much needed information about the grain size, temperature, and longevity of these structures. Recent attenuation tomography from normal modes (Talavera-Soza et al, 2025) is in good agreement with attenuation observations from body waves and surface waves in the upper mantle (Dalton et al, 2008), but appear to diverge in the lowermost mantle. In particular, normal modes observe LLVPs to be weakly attenuating, whilst regional body wave studies have observed the opposite (Romanowicz, 1998; Hwang & Ritsema, 2011; Liu & Grand, 2018).

We have made a new dataset of over 100,000 high quality measurements of ScS-S differential body waves to estimate the attenuation in the lower mantle. We have benchmarked two different methods to measure attenuation for S/ScS data, waveform matching and the instantaneous frequency matching. Within these methods, we test the effectiveness of recovering $\delta t^*$ values for the lowermost mantle from synthetics; specifically accounting for de/focussing caused by elastic structure. We invert for a 1D profile of Q for the mantle and present some initial observations of regional differences and LLVPs.

## J02 Joint models of magnetic, seismic, and other geophysical data to unravel the geological structure, constraints for georesources, and triggers for strain localization and seismicity

### AS25-0139

# Mantle serpentinization at rifted margins: insights from West Iberia and the Tyrrhenian Sea using seismic imaging and Vp tomography

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Major sites of currently active serpentinization production are slow and ultra-slow mid-ocean ridges (MORs). At magma-poor margins, serpentinization takes place during mantle exhumation at the Continent Ocean Transition (COT), a phase occurring after continental breakup and before the establishment of a steady-state oceanic ridge. During this process, mantle rocks become intensely serpentinized as they interact with seawater that percolates through cracks and faults. However, the precise sequence of serpentinization formation in these regions remains still a topic of debate.

In this study, we examine two well-known examples of mantle exhumation: the West Iberia margin, using the FRAME-P3 profile, and the Tyrrhenian back-arc basin, analyzed through the MEDOC-6 profile. Both profiles were recently acquired with high-resolution multi-channel seismic (MCS) data and are complemented by previously modelled wide-angle seismic (WAS) data. This integration significantly enhances the P-wave velocity model, providing a more detailed and refined view of the basement structure and challenging previous interpretations. The improved model offers better velocity resolution, particularly in regions with complex subsurface structures, and delivers a comprehensive characterization of the transition zone between the oceanic crust and exhumed mantle.

This analysis revealed unprecedented details such as the extent of serpentinization and the detection of a continuous reflector indicative of a hydration front. They also highlight significant fluid-rock interactions and serpentinization processes in the region. In addition, the time-migrated MCS seismic section provides a detailed view of the tectonostratigraphic framework of the COT transition.

## AS25-0450

# Vertical geofluid volume fraction profile through the seismic swarm zone in NE Japan, inverted from electrical resistivity and P-wave velocity

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We have developed an original inversion code to quantify the crustal geofluid volume fraction and salinity from electrical resistivity and seismic P-wave velocity models. The inversion code is applied to the seismic swarm area beneath Fukushima-Yamagata prefectural border, NE Japan (Okada et al., 2015; Suzuki et al., 2020; Yoshida and Hasegawa, 2018), which turned active after the 2011 Tohoku-Oki Earthquake. The seismic swarm and S-wave reflectors lie in 2–11 km and 13–14 km depths.

To apply the inversion code to the seismic swarm area, we reanalyzed the regional three-dimensional crustal electrical resistivity model of NE Japan using the magnetotelluric response and geomagnetic transfer function at 134 stations in 30–1.465×10 -3 Hz. This study's obtained electrical resistivity model, the seismic P-wave velocity mode of Okada et al. (2015), and the subsurface temperature model of Matsumoto et al. (2022) are used as the input to the inversion.

The inversion reveals that the water content begins to increase at a depth of 12 km as depth profound and attains 3.8 vol.% at a depth of 19 km. The depth of 12 km corresponds to the lower boundary of the seismic swarm region and where S-wave reflectors concentrate. The depth is interpreted as the shallowest depth of the impermeable valve in the fault-valve model proposed by Sibson (1990; 2020).

## AS25-0459

# Geomagnetic data modeling for the Kazichene-Ravno Pole geothermal region in Bulgaria

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Modeling of geomagnetic field anomalies provides critical insights into thermal sources in the Earth's crust. These anomalies result from changes in the magnetic properties of rocks, typically shaped by tectonic activities, volcanic formations, or hydrothermal changes. Similarly, geothermal anomalies, which reflect variations in subsurface temperatures, are often associated with these geological processes.

Kazichene and Ravno Pole are villages located in the western part of the Sofia sedimentary basin. This region boasts numerous hot mineral springs with significant capacity that have long been utilized for local heating. Current economic demands make the area attractive for investment in large-scale industrial geothermal energy extraction. This requires extensive geological and geophysical surveys to assess its potential.

In the present research, we investigate the magnetic field anomalies in a broader area surrounding the Kazichene–Ravno Pole site, aiming to identify the thermal source bodies. Processed magnetic data show an extensive negative anomaly of the Sofia graben, where a local variation of approximately 400 nT is observed. A small isometric anomaly is found very close to Kazichene village. Further analysis of the vertical anomaly reveals significant magnetic sources located to the south, associated with the large Brezovo-Plana magnetic chain. The potential sources are Upper Cretaceous magmatic intrusive and effusive bodies that form the Vitosha and Plana plutonic structures of fracture type. The average depths of the substantial magnetic bodies range from 3 to 7 km, as indicated by the Euler deconvolution solutions.

## AS25-0597

# The fine structure of coseismic electromagnetic response based on geomagnetic and seismological observations

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We examine the response in geomagnetic field variations caused by the 2020–2024 earthquakes with magnitudes Mw ≥ 7.0. A detailed comparison of high-precision observations of the geomagnetic field and seismograms recorded at complex geophysical observatories within a radius of 3000 km from the epicenters was carried out. The joint analysis involves averaged 1-s data on the rate of change of the magnetic field and records from broadband seismic stations. Their characteristics are assessed in both time and frequency domains. The spectral characteristics of body and surface waves are separately compared with those of the geomagnetic signal. It is shown that the beginning of disturbance in the magnetic field at each observatory strictly coincides with the arrival of the P-wave and intensifies with the arrival of S-waves. The maximum geomagnetic disturbance is caused by surface waves. The amplitude of electromagnetic excitations is proportional to the amplitude of the parent seismic phases. Thus, the coseismic nature of the observed electromagnetic signal has been confirmed, suggesting its excitation in the Earth's crust as seismic waves propagate.

## AS25-0630

# Results of the LouMu Project – Muography in the Lousal Mine

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The exploration of muography as a geophysical survey technique was the aim of the LouMu Project. As a collaboration between the Portuguese institutes of LIP, University of Évora, Ciência Viva Lousal and LNEG, the work focused on developing and testing the instrumentation and on the application of muography in an underground environment.

The survey was carried out at the abandoned and later requalified Lousal Mine, located in the Alentejo region (Iberian Pyrite Belt). The muon telescope was placed inside a storeroom of the uppermost gallery, at 18 m below the surface. A regional geological fault (Late Variscan Corona Fault) crosses the site, forming a division between two different lithologies. The structural and rock density contrast that arose from the tectonic movement were the main targets in the 45x45 $m^2$ of the muography surveyed area. The muon telescope, equipped with 4 robust RPC detectors measuring 1x1 $m^2$, tracked in real time the muons crossing the ground above, from the attenuation of which muographs were obtained. After their analysation, the identification of the Corona fault zone and the contrast in the rock densities were successful.

Alongside that, a conventional geophysical survey was carried out using photogrammetry, terrestrial Lidar, seismic tomography and georadar to describe the surveyed terrain. It resulted in a 3D geological model that served as a reference for interpreting and comparing muography data. At the same time, outreach work was performed at conferences, schools and group activities to share and raise the knowledge about the muography potential for geophysical applications.

## AS25-0637

# Integrated Seismic, Controlled Source Electromagnetic, and Magnetotelluric Imaging of Magma-Poor Rifted Margins: An Example from the Goban Spur Margin

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The final stages of magma-poor continental breakup involve mantle exhumation, serpentinisation, and increasing magmatism before the formation of oceanic crust. However, distinguishing between exhumed continental and oceanic mantle and quantifying mafic melt addition remain challenging using seismic P-wave velocities alone. Electrical resistivity measurements offer a complementary approach, as serpentinised mantle is more conductive than mafic crust, and oceanic lithospheric mantle is generally more conductive than its continental counterpart.

To address these challenges, we conducted a multi-physics geophysical survey in September 2023 at the Goban Spur margin, southwest of the UK. We acquired co-located wide-angle seismic, controlled source electromagnetic (CSEM), and magnetotelluric (MT) data along a 200 km profile, coincident with an existing high-quality seismic reflection profile. We deployed 49 seafloor instruments at ~4 km spacing, most of which recorded seismic, electric field, and magnetometer data, with two additional instruments recording inline electric fields on 200 m dipoles.

Seismic tomography reveals a sharp transition from >10 km-thick continental crust to 4–5 km-thick exhumed serpentinised mantle. This transition coincides with a lateral resistivity decrease in the mantle, inferred from MT data, with resistivity values suggesting the presence of partial melt in the asthenosphere further seaward. Furthermore, the lithosphere beneath the continent-ocean transition appears thinner than expected for a margin of 100–125 Ma, consistent with a regional surface wave model and potentially linked to small-scale convection driven by temperature contrasts at the continental edge.

## AS25-0668

# Integrated Geophysical Analysis of the Campos Basin: Unraveling Crustal Architecture, Thermal Regime, and Implications for Petroleum Systems

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The Campos Basin, situated on the southeastern Brazilian margin, is one of the most prolific petroleum basins in the South Atlantic, hosting giant oil fields. Its evolution is closely tied to the rifting and subsequent drifting phases of the South Atlantic opening (~120 Myr), which created a complex crustal architecture characterized by thick sedimentary sequences, extensive magmatic activity, and structural inheritance from pre-existing tectonic features. Despite decades of exploration, significant uncertainties persist regarding the deep crustal structure, basement relief, and lithospheric heterogeneity, all of which directly influence petroleum system modeling and resource assessment. In this study, we integrate multiple geophysical datasets—including marine magnetic and gravimetric data, post-depth migrated 2D seismic lines extending to depths of 15 km, and bottom-hole temperature measurements from over 1,200 oil wells—to enhance the understanding of the basin's crustal framework. Seismic and well log markers provide structural horizons that guide gravity and magnetic modeling, enabling a more precise assessment of sediment thickness, basement relief, Moho depth, and crustal segmentation. Additionally, heat flow data evaluate the thermal regime, critical for understanding lithospheric cooling, magmatic events, and their impact on hydrocarbon generation. The integration of these datasets offers a comprehensive perspective on the Campos Basin's geodynamic evolution, highlighting the role of inherited structures in basin formation, the distribution of crustal heterogeneities, and their implications for petroleum system development. By refining the understanding of crustal segmentation and tectonic reactivation processes, this study provides valuable insights for georesource exploration in one of the world's most significant passive margin basins.

## AS25-0708

# Magnetic and gravity mapping to the SW of Salamanca (Central Iberian Zone): insights on the tectonic context and mineral deposits

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The western part of the Central Iberian Zone features long-wavelength, high-amplitude magnetic anomalies that coincide with gneiss domes cored by non-magnetic granites, e.g., Central System Magnetic Anomaly and Porto-Veira-Guarda Magnetic Anomaly (PVGMA). They both overlap the W-Sn belt, a puzzling fact as the redox potential of Sn ores requires contexts without magnetite.

Aiming to unravel the relationship between magnetic anomalies and Sn ores, to shed light on the origin of mineralization, and to reveal the source of the reverse polarity Salamanca magnetic anomaly (SAMA), high-resolution potential field maps to the SW of Salamanca are being acquired.

Preliminary results show a conspicuous image of the NE-SW, long active, Alba-Villoria Fault. The SAMA largely coincides with a gravity maximum, but does not show much relationship with the non-magnetic surface rocks, i.e., the outcropping Ordovician slates randomly present a reverse polarity remanence compatible with the SAMA, but with very low intensity. To the S, layers of magnetic slates explain some short-wavelength maxima that appear in the map, but are not capable to produce the SAMA or the PVGMA. Finally, a clear relationship exists between gravity/magnetic maxima and high shear-wave velocities to the W, in areas close to Sn-W ores. Although gravity maxima often coincide with Late-Proterozoic and Lower-Cambrian outcropping slates, these are not magnetic, so the question about the origin of the magnetic anomalies remains. Thermal metamorphism in relation to the intrusion of igneous rocks or the existence of different magnetic lithologies at depth are possible interpretations. Acknowledgments: SA066P24 from the JCYL

## AS25-0756

# Geothermal Resource Evaluation and Public Awareness for Sustainable Energy: Case Studies from Southern Italy

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This study investigates geothermal resource potential in two key areas of Southern Italy: Contursi Terme (Campania Region) and Tramutola (Basilicata Region) characterized by thermal fluid circulation and complex geological settings. Contursi Terme hosts over 77 thermal springs and numerous wells used for balneotherapy, while Tramutola is known for a confined aquifer associated with relatively shallow hydrocarbon reservoirs, where mantle-derived gases were detected.

A multi-parametric geophysical approach was adopted to characterize subsurface structures and identify geothermal reservoirs. ERT mapped near-surface conductive anomalies related to hydrothermal fluid flow, while MT soundings detected deep low-resistivity layers, suggesting the presence of geothermal reservoirs within carbonate-evaporitic units. Additionally, ambient seismic noise analysis provided constraints on lithological variations and the geometry of fluid-bearing formations. The results confirm that fault-controlled permeability enhances geothermal fluid migration, supporting the potential for sustainable energy exploitation.

Beyond scientific research, this work highlights the role of public engagement in geothermal energy development. Field campaigns and outreach initiatives demonstrated the low environmental impact and societal benefits of geothermal resource utilization. This integrated approach contributes to resource assessment, regional energy strategies, and the broader energy transition towards sustainable alternatives.

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## AS25-0802

# Evaluating Models for the Genesis of Low-angle Normal faults: A multidisciplinary study of the Cañada David detachment, Baja California, Mexico

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The LSB is controlled by the Cañada David Detachment (CDD), which is a seismically active low-angle normal fault that extends 55–60 km along-strike and roots westward beneath the Sierra Juarez. Low-angle normal faults (LANFs) are important structures in extensional settings throughout the world, but their genesis and mechanics of slip remain poorly understood. In order to test widely applied genetic models of LANFs we present a multidisciplinary study that combines gravimetry, magnetotellurics, seismic reflection profiles, earthquake seismicity, borehole logs, geological mapping, and tectonic geomorphology to construct three 2-D profiles of the crustal structure and subsurface geometry of the CDD. We find the CDD to cut the seismogenic crust to depths of 15 km with a flat-ramp-flat geometry and crustal profiles show a 150% thickening of the lower crust beneath the CDD ramp, suggesting isostatic compensation driven by lower crustal flow. Variations in topographic relief and drainage basin geomorphology suggest that antiformal megamullions are uplifting at significantly higher rates, indicating that they formed by folding of the detachment in response to constrictional strain. Synformal megamullions are domains where surface faulting has migrated into the basin to form new rider blocks of the detachment system. These findings are consistent with the rolling-hinge model of detachment faulting.

## AS25-0901

# High-resolution seismic characterization in Monchique, SW Iberia

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The Monchique Alkaline Complex is an intrusive igneous massif of magmatic origin, with an approximately elliptical shape oriented East-West, associated with Upper Cretaceous alkaline magmatism. The region hosts the most seismically active cluster in mainland Portugal, although the events have low magnitudes (M<4.0). Previous studies reveal two main lineations, oriented NNE-SSW and E-W, which show no direct correlation with mapped geologically active faults.

This study presents a seismic catalog generated using automatic methods, based on data from 23 temporary stations (Oct 2018-May 2021) and permanent stations. Events were detected with Lassie, using constant P- and S-wave velocities. Hypocenters were refined with LOKI, using a 3D velocity model and selected waveform segments with initial arrival times estimated by Lassie. We next used PhaseNet to estimate P- and S-wave arrivals, followed by a quality control step to filter out events unsuitable for the final relocation, performed with NLL-SSST, which applies a non-linear probabilistic inversion combined with a systematic arrival-time correction, using both the 1D and 3D velocity models. Finally, we relate seismic activity to the geophysical modeling of the Monchique intrusion.

Our analysis highlights the need for effective strategies to distinguish real from false detections in automatic seismic methods. Vertical location accuracy showed significant limitations through Lassie, but applying LOKI improved the agreement between seismic manual locations and those obtained through automatic methods, successfully capturing key seismogenic structures. Some scattered events showed higher variability.

## AS25-0952

# Influence of elastic rock properties on megathrust dynamic rupture and coseismic upper-plate deformation

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Accurately determining upper-plate physical properties is essential for constraining coseismic deformation and dynamic rupture parameters in subduction zones. This study integrates 3D tomographic models, seismic imaging, and visco-plastic dynamic rupture simulations to investigate how these properties influence earthquake dynamics and upper-plate coseismic deformation.

The first component presents 3D P-wave velocity structures and interplate geometry offshore the Colombian-Ecuador margin. Low-rigidity regions, identified through a Monte Carlo-based inversion, suggest enhanced fracturing above the interplate. These features, shaped by crustal-scale faulting and local geology, may promote localized coseismic slip and seafloor uplift during rupture.

The second component explores the influence of elastic rock properties on off-fault deformation through dynamic rupture simulations for Japan, Chile, and Sumatra subduction zones. These simulations incorporate rate-and-state friction laws and bulk cohesion dependent on shear modulus derived from tomographic models. Despite variations in coseismic slip and uplift across regions, deformation consistently localizes near the compliant frontal region, which absorbs fracture energy from the main fault, causing internal deformation of the upper plate while limiting slip along the primary megathrust fault.

By integrating these approaches, this study underscores the importance of understanding both along-strike and depth-dependent variations in upper-plate properties from controlled-source seismic experiments to constrain how the upper plate deforms and transmits energy during large megathrust earthquakes.

## AS25-0957

# Integrated geophysical studies for characterization of offshore wind farm areas off the West Portuguese coast

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The Portuguese Institute for the Sea and Atmosphere (IPMA) is developing extensive high-resolution geophysical and geotechnical studies over two areas proposed for the development of offshore windfarms (OWF). Approximately 2000 km$^2$ are being studied in Leixões and Figueira da Foz areas (depths of 120 m and 530 m; 21 nm to 35 nm from the coastline). Given the margin characteristics floating turbines are required, and the engineering solutions to be implemented will depend on the local geology.

The project aims to provide detailed data and interpretation on the morphology, geology, geophysics and geotechnical properties of the seafloor to help/support OWF developers towards engineering strategies.

In 2024, two surveys provided exploratory data to plan subsequent campaigns: 1) a survey for multibeam echosounder acquisition (bathymetry and backscatter) and surface sediment sampling; 2) a survey that collected >2100 km of seismic data, including parametric sub-bottom profiler and ultra-high resolution seismics. A first geomodel for each area was produced based on seabed morphology, sediment textural features, mapping of seismic horizons and geohazards.

In 2025, a new survey will expand 10 times the line density of the 2024 seismic datasets, including additional methodologies (magnetometer, side scan sonar, vibrocorer and CPTs) to improve the geological and hazard mapping of the areas. This pioneering effort in Portugal's energy transition will provide crucial data for the sustainable development of offshore wind energy.

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## AS25-1065

# Tsunami source inversion of the 2024 Hyuganada (Japan) earthquake using high-frequency ocean radar

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On 8 August 2024, at 07:42 UTC, a Mw 7.1 earthquake occurred in the Hyuganada Sea off the coast of Miyazaki Prefecture, Japan. The earthquake triggered a tsunami, which peaked about 40 minutes after the earthquake, with a maximum height of about 40 cm. After this earthquake, JMA issued an unprecedented public advisory on higher-than-usual risks of a megaquake in the Nankai Trough.

We conducted a joint inversion of the source of the 2024 Hyuganada earthquake using offshore bottom pressure gauges (OBPGs), tide gauges, and high-frequency (HF) radar. The OBPGs belong to the N-net, extending from offshore Kochi Prefecture to Hyuganada Sea. The HF radar is installed along the coast of Miyazaki Prefecture (frequency: 13.5 MHz). We set up 25 subfaults, each with a size of 12 km × 12 km. Green's functions were computed between the subfaults and tsunami observational points (height or velocity). We estimated the slip distribution using non-negative least squares regression.

The magnitude of the finite fault model obtained from the joint inversion is generally consistent with that obtained from seismic wave inversion, but the model provides better tsunami simulation results. Additionally, after including the HF radar data, the fit with the tide gauge on the Kyushu coast (west of the fault) improves. The main innovation of this study is the introduction of HF radar for tsunami source inversion. It demonstrates that current velocity data can also be used in inversion, allowing for a more diverse set of data in source inversion.

## AS25-1072

# The seismic velocity and tectonic structure of the Africa-Iberia plate boundary region across the Tore-Madeira Rise

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The LISA-ATLANTIS cruise was conducted in 2022 onboard the Spanish R/V Sarmiento de Gamboa. Wide-angle seismic reflection and refraction data (WAS) and coincident multichannel streamer data (MCS) were collected to constrain the seismic velocity structure west of the Gorringe Bank, where the nature and structure of the lithosphere are mostly unknown.

WAS data were acquired using 21 ocean bottom hydrophones (OBH) spaced at ~15 km, along a NNW-SSE oriented, ~400 km long profile, at 250 Hz sampling frequency. The seismic source consisted of two sub-arrays of 16 airguns with total volume of 5200 c.i., towed at 15 m depth. MCS data were acquired with a 6 km long streamer towed at 23 m depth.

OBH sections were analyzed for identification of Ps, Pg, PmP and Pn phases, and show high variability along the profile. Joint inversion of refraction and reflection travel times of key boundaries observed in WAS and MCS data were used to build a final P-wave velocity (Vp) model, following a layer stripping strategy, and Vp uncertainty was evaluated using Monte Carlo analysis.

The LISA profile crosses the Africa-Iberia plate boundary across the Tore-Madeira Rise, the west Horseshoe Abyssal Plain, and the Ampère seamount. Results show a complex velocity distribution with implications for the geodynamic evolution of this region of the Atlantic and West Iberia margin and for plate boundary deformation processes.

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## AS25-1080

# Connection of earthquakes with high-conductive structures in the middle crust in the eastern Slovakia

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The territory of Slovakia is formed by the orogenic system of the Western Carpathians, which is part of the Alpine-Himalayan young orogenic belt. This orogenic system, created mainly during the Miocene and Pliocene, is tectonically active until today. The consequence is also frequent seismic events. The area of eastern Slovakia is also seismically active, but the earthquakes here have different features from those in other parts of the Western Carpathians. To illustrate this specificity, we used the course of the last relatively strong (M 4.9) earthquake in this area from October 2023. Magnetotelluric modelling on the profiles in the eastern Slovakia suggests very large electrically high-conductive layers in the middle and lower crust. Such layers are generally interpreted as fluid-enriched zones with the presence of partial melt that rapidly increase conductivity. In the area of eastern Slovakia, these zones are the result of atsthenospheric masses interaction with the crust, which led to increase of heat flow ,volcanic activity and accumulation of fluids. Fluid overpressure in the crust, in addition to the kinematic components during the release of tectonic stress, is considered generally in the scientific works as one of the main drivers of seismic processes. Earthquake from October 2023 we interpret as possible influence of overpressured fluids connected with highly conductive layers in the crust.

## AS25-1199

# Mapping Igneous Structures in the South Okinawa Trough by Using Magnetic Data Analysis Method

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The south Okinawa Trough (OT) is the back-arc extension basin of the Ryukyu arc-trench system, extending 1200 km east-northeast from the Ilan Plain in northeastern Taiwan to Kyushu in southern Japan. It is a product of the northwestward subduction of the Philippine Sea Plate beneath the Eurasian Plate. The south OT, located between 122˚ E to 124˚ E and 24.5˚ N to 26˚ N, exhibits major geological structures such as normal faults, volcanoes, grabens, and intrusive igneous rocks. Notably, flares and chimneys have been discovered on or around submarine volcanoes and igneous structures, indicating high tectonic activity in the area. Therefore, the distribution of igneous rocks or volcanoes plays a crucial role in understanding the extension or collision mechanisms and the geological fault system of the south OT. This study presents a novel attempt to map potential igneous structures using magnetic data, compared with reflection seismic profiles. Furthermore, we applied advanced analytic signal (AS) and Curie Point Depth analysis (CPD) to the study area to gain deeper insights into the igneous structure and geothermal conditions within the extensional setting. Finally, we will present the AS and CPD maps and discuss the tectonics, extensional activity, and volcanism of the south OT, aiming to enhance the application of magnetic methods in this field.

## AS25-1284

# Leveraging massive geophysical datasets for Hydrogen exploration: Hydrogen ORe EXploration (HOREX)

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Hydrogen (H2) is widely recognized as a key player in decarbonizing the economy, and natural hydrogen could be a game changer in this transition. In this context, the emerging industry is shifting towards a programmatic, scalable, play-based exploration strategy, requiring subsurface imaging to assess H2 prospects in a probabilistic and realistic manner. In this presentation, we introduce HOREX: a technological pilot for imaging natural hydrogen systems deployed in April-May 2025 in the French Pyrenean foothill. HOREX incorporates measurements from 1000 new-generation 3-component seismic sensors, 5000 virtual sensors from a 25-kilometer-long dark telecom optic fiber, alongside gravimeters and other non-seismic methods. The available data are jointly processed to create 3D multiphysics images of the H2 system. We describe the processing of the extensive HOREX seismic datasets for earthquake relocation and the construction of preliminary seismic images. Additionally, 3D large-scale geological models are developed to create synthetic datasets that help explore the sensitivity of key H2 system parameters. By combining these two approaches, we discuss the potential implications for H2 systems in the French Pyrenean foothills.

## AS25-1318

# Advances Towards 3D Modeling of Mineral Deposits: Stochastic Joint Inversion of Potential field (Gravity-Magnetic) and, Machine Learning Constraints

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This contribution describes a new twist on 3D model building where an integration of the stochastic inversion of gravity and magnetic data with Machine learning (ML) is carried out. 3D probabilistic physical property volumes (density; magnetic susceptibility) are determined by stochastic joint inversion of the Bouguer gravity and Magnetic anomalies. Laboratory measurements of petrophysical properties of rock samples (PPR) constitute the main database used by the advanced ML approach to resolve predictive Seismic P-wave velocity and total porosity distributions from the lab measurements of over 1000 rock samples. The 400 km² study area around Riotinto mine (Iberian Pyrite Belt, Spain) hosts one of the world's largest massive sulfide deposits. The 3D models delineate geological structures and geodomains, identifying potentially mineralized zones with high density and P-wave velocity, and low porosity. However, significant overlap in petrophysical properties among lithologies and mineralization degrees complicates discrimination.

Despite these challenges, the method identifies anomalous rock bodies (high density, high Vp, low porosity) at different depths, correlating with shallow mafic formations and compacted slates below 1,250 m. The approach enables classification and prioritization of zones based on their mineralization probability, effectively highlighting areas with high potential for massive sulfide deposits.

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## AS25-1326

# Fracture network characterization in a geological complex considered for carbon dioxide ($CO_2$) injection in the offshore of the Lusitanian Basin

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The urgency to mitigate climate change has demanded the development of innovative technologies to reduce carbon dioxide ($CO_2$) emissions. Among these technologies, Carbon Capture and Storage (CCS) involves the sequestration of $CO_2$ in deep geological formations, including deep saline aquifers (DSA).

The central offshore of the Lusitanian Basin holds significant potential for $CO_2$ storage in DSA. However, caprock integrity is a critical factor in ensuring safe and long-term storage, as fractures within the sealing formation may compromise the injection site. This study aimed to characterize fracture networks of a geological site targeted for $CO_2$ injection, using the 3D Cabo Mondego seismic data as an analogue.

Fracture interpretation was conducted, followed by a statistical analysis of the identified fractures to evaluate their distribution and properties. The fracture characterization was performed considering key parameters such as fractures' length, height, orientation (strike and dip), aspect ratio (height/length ratio of the fractures), as well as the fracture intensity within the area. This characterization allowed to evaluate the influence of fracture networks on storage integrity, identify potential leakage pathways, and assess $CO_2$ storage feasibility in the area, while addressing data limitations.

This research is aligned with the PilotSTRATEGY project, aiming to investigate DSA for $CO_2$ storage across Europe. Integration of this work with the broader project by considering fracture characterization for the simulation of long-term fate of $CO_2$ plume, provides valuable insights to the $CO_2$ storage potential, and improves the knowledge of fracture networks in deep saline aquifers.

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## AS25-1458

# Rigid crustal blocks identified by magnetic anomalies and earthquake hypocenters, and the seismic process features in their vicinity (Baikal Rift)

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Analysis of data on the hypocenters of seismic events and the distribution of magnetic field anomalies in the areas of the central and southern parts of Lake Baikal revealed several aseismic structural elements in the Earth's crust that spatially coincide with positive magnetic anomalies. For example, such an anomaly was found in the southern part of Lake Baikal. The aseismic region basically coincides with the contours of the magnetic anomaly, which makes it possible to consider this structure more rigid than the surrounding structures. It is important that all strong earthquakes with a magnitude >5 occurred only along the boundaries of this anomalous body. Another example concerns the Zarechensk batholith of Late Archaic age, which is located on the eastern coast in the central part of Lake Baikal. For this anomalous body with high magnetization, the depth of the lower edge was determined by solving the inverse problem. The depth of occurrence was 18–20 km, with good convergence of the inversion results using various methods. It is determined that the Curie temperature for gneisses of the Zarechensk magnetic anomaly is 600 °C. Since the depth of the batholith exceeds 20 km, as indicated by earthquake hypocenters along its vertical boundaries, it can be argued that the lower edge of the magnetized body at a depth of 18–20 km is the Curie boundary with a temperature of about 600 °C. It was also found that rigid bodies in the Earth's crust significantly affect the parameters of aftershock processes.

## AS25-1461

# Active Tectonics in the Ionian Realm and Implications for the Sources of Current Seismicity

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The structure across the margins of the Ionian Sea is tectonically complex, because it is under-evaluated due to a limited availability of seismic data coverage. However, the region has the most abundant earthquake activity in the Mediterranean and large events have struck it, with devastating results. Multiple fault systems are associated with dramatic changes in the current deformation rates, but their dimension, kinematics and activity are poorly known, because they are inadequately mapped.

Current knowledge cannot unequivocally differentiate whether earthquakes occur along the subduction plate boundary, or in over-riding-plate faults, or are part of a different system, let alone we can precisely define the location, geometry and extent of active plate-boundary faults.

We have gathered a seismic data base including new, reprocessed seismic data, and industry-provided seismic lines along the Ionian realm, as well as high resolution multi beam bathymetry to map those system. Recently, we have been provided with industry-quality (10.5 km long streamer) lines to study remaining regions of the margins and deep basins of the region.

Our new data set provides the first extensive coverage of the tectonic structure, and the new seismic images document abundant deformation that can not be easily explained by existing models of subduction-zone type of deformation everywhere. We propose a model in which the current tectonic activity is the result of impending collision between Africa and Europe, where the dominant geodynamic forces are not longer related to the slabs subducting under the continent, which were previously driving the evolution of the eastern Mediterranean realm.

# J03 Exploring crust and mantle beneath the oceans, solid Earth-Ocean interactions and soundscape in the oceans: innovative instrumentation, processing ocean-bottom and floating sensor data and scientific achievements

## AS25-0152

## Three-dimensional radially anisotropic upper mantle shear wave structure beneath the Pacific Ocean incorporating broadband ocean bottom data

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Understanding the coupling of deep Earth and surface processes is essential to clarify the true characteristics of Earth's plate tectonics. Surface wave tomography is a popular method to reveal the oceanic lithosphere-asthenosphere system. However, elucidating the true nature of oceanic plate evolution is still in progress, partly because most tomographic models are based solely on land stations, resulting in limited spatial resolution.

Broadband ocean bottom seismometers (BBOBS), developed since 2000, enable broadband seafloor seismic observation comparable to that on land, particularly in the Pacific Ocean. A significant milestone was the "Pacific Array" concept proposed in 2014 by Kawakatsu and colleagues. The strategy involves deploying ~15+ BBOBSs in an array unit for 1–2 years observation in a leap-frog fashion, covering the whole Pacific Ocean after a decade or so. Since 2015, international collaborations (Japan, U.S.A., EU, South Korea, Taiwan, and China) have realized this vision. Japan's observations include the Oldest-1 Array (2018–2019) with South Korea and the Oldest-2 Array (2022–2023) with Taiwan.

In this study, we revised the earlier model by Isse et al. (2019) by incorporating additional land station data from the eastern Pacific coast, along with seafloor observation data such as OJP array, Oldest-1 and Oldest-2 Arrays, while applying the tilt noise and compliance noise removal method. In the presentation, we will show the differences from conventional models, improvement in spatial resolution, and structural characteristics from the perspective of oceanic plate evolution.

## AS25-0227

# Rayleigh-wave Analysis for the OHANA Experiment in the Northeast Pacific

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The 2022–2023 OHANA OBS deployment in the northeast Pacific Ocean provides a rich dataset for comprehensive seismic studies to explore the crust, lithosphere and asthenosphere in a 600~km wide region west of the Moonless Mountains. The study area covers mainly 40-to-50 Myr old Pacific lithosphere. A fundamental question to be addressed is whether this particular area has the signature of a typical oceanic lithosphere that has a normal plate cooling history. Alternatively, we seek evidence for a previously proposed reheating process, e.g. resulting from small-scale shallow-mantle convection. Given its location, the OHANA experiment contributes crucial data to the Pacific Array initiative.

We present the analysis of path-averaged Rayleigh wave dispersion curves obtained from earthquake records as well as ambient-noise cross-correlation functions. Forward modeling and the inversion of the average dispersion across the OHANA network both indicate lower shear velocities than expected for a 50-Myr old crust and lithosphere. Velocities in the mid-to-lower lithosphere may be 2–3% lower than expected but resolution degrades with increasing depth. We observe significant and internally consistent azimuthal anisotropy in both the fundamental mode as well as the first overtone, where the 'fast direction' places between fossil and modern spreading directions.

## AS25-0245

# Characterizing microseism sources in the Indian Ocean: Advances from Ocean Bottom Seismometer studies

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Indian Ocean serves as a prime example of closed ocean system, where the strongest microseisms have been traditionally attributed to the intense Southern Ocean processes. This somehow undermines the role of potential coastal reflections generated from the adjoining landmasses. Here, by utilizing a large array of ocean bottom seismometers, we investigate the role of coastal over Southern Ocean processes in generating microseisms in the Indian Ocean. By integrating a multidisciplinary approach such as single station polarization, power spectral density, correlation analysis along with numerical wave modelling and attenuation analysis, we characterize microseisms and their potential sources. Our study reveals that the coastal reflections appear to dominate the strongest deep Southern Ocean seismic noise in the Indian Ocean. Such anomalous behavior, which is contrary to the prevailing views of the microseism in the Indian Ocean is mostly attributed to the propagation path effects. Our results also show that the strongest secondary microseisms are generated during the simultaneous development of cyclones in the opposite hemispheres. These findings have vital implications towards the way we characterize and quantify the seismic noise in the closed ocean systems. This study underscores the need to reconsider the fundamental drivers of seismic noise in oceanic environments, particularly in the context of a changing climate where cyclone activity and intensity are projected to increase.

## AS25-0246

# Bridging gaps in mantle dynamics: Insights from the Indian Ocean Geoid Low Programme

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The Indian Ocean Geoid Low (IOGL), the most prominent high-amplitude (40 to 106 m) geoid deficit on Earth, offers a unique window into the complex dynamics of the Earth's mantle. While existing hypotheses link this anomaly to low-density, low-velocity anomalies in the mid-to-upper mantle and high-velocity anomalies near the base of the mantle, the precise mechanisms driving these features remain poorly understood. To address this, we deployed an extensive array of Ocean Bottom Seismometers (OBSs) across the IOGL. Here, we present an updates on the understanding of mantle structures and dynamics from the OBS datasets utilizing Receiver functions and surface wave Analysis. The work presented here discuss a revelation of 800 km wide depression in the mantle transition zone for both the d410 and d660 beneath the IOGL and its uncertainties. Excess temperatures and shear wave velocity anomalies suggests hot mantle upwelling, likely driven by the deep-seated processes. Rayleigh wave phase velocity variations within the period range of 15–197 s reveals a prominent low-velocity zone in the upper mantle. A thicker low-velocity zone and thinner lithosphere, indicates a hot thermal regime in the upper mantle. By addressing critical gaps in our understanding of mantle dynamics, such work could pave the way for future research that integrates seismic, geochemical, and geodynamic models beneath the oceans. Future prospects hinges on integrating OBS networks from different oceanic sectors, advanced modelling, and mantle-surface observables to refine global mantle dynamics models.

## AS25-0292

# Quantitative constraints on the thermal and compositional states for old oceanic mantle in the northwestern Pacific from marine magnetotellurics

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Oceanic upper mantle beneath the northwestern Pacific has large-scale lateral heterogeneity that is impossible to attribute to an age-dependency of the thermal structure based on a simple cooling of the lithosphere. This fact was revealed from seafloor magnetotelluric (MT) data collected in two areas, northwest (Area A) and southeast (Area B) of the Shatsky Rise, through Normal Oceanic Mantle Project. We considered one-dimensional thermal structures based on three different cooling scenarios: 1) a plate cooling with age, 2) a half-space cooling with apparent age representing rejuvenation, and 3) a cooling with small-scale convection, respectively, with a reasonable mantle adiabat. The grid search inversion approach guarantees that the preferred model parameters constraining the thermal structure and the volatile ($H_2O$ and $CO_2$) contents in the bulk mantle can explain the observed MT data and enable us to investigate the quantitative trade-off relations between the parameters.

From the inversion analyses, we quantitatively verified that the thickness of the thermally conductive layer significantly thinner for Area A than for Area B as qualitatively suggested by the previous study (Baba et al., 2017). With reasonable potential temperature (1350±30 degree C), small amount (<160 ppm) $H_2O$ is necessary, small amount (several tens ppm) of $CO_2$ likely exists, and possible melt fraction is very small (<0.06 vol%) in the mantle beneath the areas, which is compatible with the depleted source mantle that is the origin of the normal oceanic crust. However, the consistency between the MT data and the water depths needs more careful examinations.

## AS25-0569

# Advancing passive seismic imaging in deep marine environments: insights from the Gulf of Lion

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The Gulf of Lion, located in the northwestern Mediterranean Sea, is a back-arc basin that opened during the Miocene while the Corsica-Sardinian bloc detached from the main European plate. It is a natural laboratory for studying geological processes that shape continental margins and new oceanic basins. In the region, the transition from continental to oceanic domains, especially regarding the nature of the crust, is a subject of significant debate.

Seismic imaging is a fundamental tool for investigating subsurface properties. Traditionally, these methods rely on active sources, which, despite their effectiveness, involve significant financial, logistical, and environmental constraints. In contrast, passive seismic imaging provides a sustainable alternative by using naturally occurring ambient seismic noise, eliminating the need for artificial sources while offering insights into the Earth's interior.

This PhD research applies passive seismic imaging to data collected during a 42-day-long ocean bottom seismometer (OBS) deployment in the deep waters of the Gulf of Lion in 2024. Using ambient noise tomography (ANT), we aim to infer seismic velocities in the sediments and basement and correlate them with results from earlier active seismic experiments. While ANT is widely used for imaging the crust and uppermost mantle from continental stations, its application to OBS data is limited. Recent studies have demonstrated the potential of ANT with OBS data, yet key logistical and methodological challenges remain. This research will refine methodologies for marine ANT and provide new constraints on the structure of the Gulf of Lion margin.

## AS25-0709

# Rayleigh wave azimuthally anisotropic phase velocity maps of the lithosphere-asthenosphere beneath the oldest Pacific plate using ocean bottom seismic array

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The lithosphere-asthenosphere system beneath the oldest Pacific plate remains poorly understood due to limited seismic observations in this remote region. The Oldest-1 Array (2018–2019) revealed significant variations in the oldest (170–180 Ma) Pacific seafloor, including a well-resolved transition between the high-velocity lithosphere and low-velocity asthenosphere at depths of 80–100 km, and distinct azimuthal anisotropy patterns between western and eastern regions (Kawano et al., 2023). Building on these findings, we deployed the Oldest-2 Array westward across the Ogasawara Fracture Zone to investigate the shear velocity structure and azimuthal anisotropy in this tectonically complex boundary area. Following the Japan-Korea Oldest-1 Array, Oldest-2 represents a Taiwan-Japan collaboration with 12 BBOBS stations (9 ERI, 3 IES) operating from September 2022 to October 2023. Using teleseismic Rayleigh wave dispersion measurements from 30 high-quality events, we obtained robust phase velocity maps for periods between 20–150 seconds from vertical component data and 20–50 seconds from pressure data. Our preliminary results reveal a relatively uniform lithospheric thickness of approximately 100 km with a moderate low-velocity zone between 190–250 km depth. The azimuthal anisotropy analysis shows consistent patterns with fast directions predominantly oriented around 100° at shorter periods (20–40s), with strength variations between 1–4% across the study area. We observe spatial variations in anisotropy strength and slight rotations in fast direction with increasing period, suggesting depth-dependent fabric changes in the lithosphere-asthenosphere system beneath this ancient portion of the Pacific plate.

## AS25-0784

# From Floats to Gliders: Advancing Marine Seismology with Autonomous Underwater Vehicles

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Seismic monitoring in oceanic regions remains a significant challenge due to the high costs and logistical complexities of traditional instrumentation. This study explores the feasibility of using ocean gliders for earthquake detection, based on six years (2015–2021) of passive acoustic data from the Santos Basin Underwater Soundscape Monitoring Project (PMPAS-BS) in southeastern Brazil. Ocean gliders, autonomous vehicles that adjust buoyancy and steer via internal mechanisms, enable energy-efficient, long-term monitoring of specific oceanic areas via predefined routes. Initially deployed for underwater soundscape studies, including marine and anthropogenic noise monitoring, the gliders unexpectedly detected low-frequency seismic signals, identifying 12 potential earthquake events. Of these, 11 corresponded to teleseismic sources, including mantle and core-transmitted phases, while one event was a regional earthquake. An automated methodology combining spectral analysis and short-term to long-term average (STA/LTA) ratio triggering was applied to detect and validate these events. Notably, the recognition rate for global earthquakes with magnitudes above 6.0 was approximately 9%, with epicentral distances ranging from 21 to 155 degrees. Despite not being initially designed for seismic monitoring, the gliders demonstrated promising capabilities, even while managing short recordings and overcoming internal and external noise sources. Their ability to integrate various sensors for multidisciplinary monitoring, coupled with near-real-time communication via Iridium satellite connections, makes them highly versatile. These findings underscore the potential of ocean gliders to address observational gaps in marine seismology, offering a cost-effective and adaptable tool for future earthquake monitoring initiatives in offshore regions.

## AS25-0841

# Megathrust heterogeneity revealed by Electromagnetic data at the Shumagin segment of the Aleutian-Alaska Subduction Zone

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Understanding the key mechanisms governing megathrust slip behavior and seismic activity is critical for advancing our knowledge of subduction zone processes and mitigating associated seismic hazards. However, limited near-trench seafloor geodetic observations have resulted in substantial uncertainties about shallow slip behavior in most subduction zones globally. Fluids have been considered to profoundly influence or control megathrust plate coupling. In this study, we use controlled-source electromagnetic (CSEM) data to provide new constraints by imaging the electrical resistivity structure of the shallow megathrust and forearc region in the Shumagin Gap, a known creeping segment of the Aleutian-Alaska subduction zone. Our inversion results reveal pronounced trench-normal heterogeneity in the electrical resistivity of both the shallow plate interface and the forearc overriding plate, indicating substantial lithological and fluid-content variations within the subduction system. The limited fluid presence along the plate interface inferred from our resistivity model suggests that fluids alone are insufficient to fully account for the observed creeping slip behavior. Consequently, high fluid pressure along the plate interface is unlikely to be the primary driver of weak coupling in this area. Rather, our findings highlight the complex geological heterogeneity and fluid distribution likely govern the shallow slip behavior in the Shumagin segment. Our approach complements previous seismic and magnetotelluric studies and integrates seismic observations. Our results underscore the necessity for advanced near-trench seafloor instrumentation and a comprehensive multidisciplinary strategy to better understand the complexities underlying subduction zone seismogenesis.

## AS25-0972

# Ocean bottom monitoring solutions: autonomous nodes, cabled observatories and SMART cables

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Autonomous free-fall OBS units allow users flexibility in deployment and the ability to redeploy in different locations. The Aquarius functions at any angle without using a gimbal system, and can wirelessly transmit SOH and seismic data to the surface via an integrated acoustic modem. These features allow researchers to monitor and transmit data packets without offshore cabling, reducing logistical challenges whilst maintaining some degree of real-time data transmission. This broad functionality and connectivity has made the Aquarius well-suited for OBS pool use, such as with the National Facility for Seismic Imaging in Canada.

Alternatively, cabled solutions provide access to high-resolution data in real time via a physical link to on-shore infrastructure. As an example, the Orcus provides a complete underwater seismic station with an observatory-grade seismometer and a strong-motion accelerometer in a single package. The slimline Maris uses the same omnidirectional sensor as the Aquarius and can be installed either on the seabed or in a narrow-diameter subsea borehole. Both systems are deployed globally as part of multi-disciplinary observatories such as the Neptune array operated by Ocean Networks Canada.

SMART cables offer great potential for increasing marine observation with substantially reduced deployment costs. Combining several applications into a single system, including seismology, oceanography and telecommunications, large scale monitoring networks can be created cost-effectively by combining logistical and fundraising efforts from multiple industries. A wet demonstration SMART Cable system in the Ionian Sea in collaboration with Instituto Nazionale Di Geofisica e Vulcanologia (INGV) is the first practical demonstration of this technology.

## AS25-1034

# Signals from self-calibrating Bottom Pressure, seafloor marine energy cables and ocean bottom seismometers to understand the solid Earth and oceans

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Ocean bottom instrumentation at the liquid – solid interface record both oceanographic and solid Earth phenomenon. We present results from self-calibrating bottom pressure recorders (AZA), marine energy cables using distributed acoustic sensing (DAS), and four component ocean bottom seismometers (OBS). We show how the AZA records deployed near tall moorings in the Atlantic offshore the Bahamas record surface tides, internal tides, sea surface height changes, and instrument subsidence (with the potential to infer properties of underlying sediments). We discuss implications for constraints on changes in large scale current changes, with climate implications and seafloor geodesy with implications for tsunamigenic hazards. The DAS cables show evidence for ocean gravity waves and recordings of nearby vessels. We present a means of determining the burial state of these cables based on the strain response of the cable to the vessel recordings, an important factor in assessing potential cable hazard. Finally, observations from OBS host a range of environmental and solid Earth signals from the PI-LAB and VoiLA experiments. At PI-LAB we image interesting and unanticipated lithosphere-asthenosphere structure beneath the equatorial Mid-Atlantic Ridge, including a lithospheric drip and an asthenospheric a melt channel. At VoiLA we image unexpected fluid pathways through the mantle wedge of the Lesser Antilles subduction zone. Overall, there is much promise for large-scale, interdisciplinary ocean bottom observatories to study the oceans and the solid Earth in the future.

## AS25-1043

# Impact of OBS and MERMAID observations on the location accuracy of remote oceanic earthquakes

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Many of the world's most seismically active plate boundaries and fault zones are under the oceans, and their remote settings often mean that precise locations of these earthquakes are poorly constrained. The lack of nearby stations means that locations often rely exclusively on tele-seismic observations, limiting the horizontal resolution of the earthquake location, and providing limited constraint on earthquake depth and origin time. Oceanic seismic deployments are one of the only ways to mitigate our lack of knowledge about the location and depth of remote oceanic earthquakes. We consider three case studies of remote oceanic seismicity that occurred either at subduction zones or spreading ridges and are recorded by OBS or MERMAID seismometers. By considering the earthquake location accuracy with and without these submerged ocean stations, we quantify the impact of local and regional OBS observations on earthquake location uncertainty. The first example concerns seismicity from the Tonga subduction zone recorded by OBS from the 1994 LABATTS project. In the second example we apply automated pickers to waveforms from the RHUM-RUM OBS deployment to improve earthquake locations for the Southwest Indian Ridge. In the third example we quantify the impact of MERMAID observations on earthquake locations in the Tonga region. We show that even relatively sparse deployments that only add limited phases within 1000 km still bring improvements in the horizontal accuracy of earthquake locations, while depth resolution may only be improved by more dense deployments.

## AS25-1044

# Imaging the oceanic lithosphere beneath the Gulf of Cadiz

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The Gulf of Cadiz is an area of diffuse convergence between the Eurasian and the Nubian plates, in the westernmost section of the Gibraltar Arc. To image the structure of the lithosphere using P-wave receiver function analysis, we use 12 ocean-bottom seismometers (OBS) deployed from 2007 until 2008 within the EU funded project NEAREST (integrated observation from NEAR shore sourcES of Tsunamis). After removing the water-layer multiples by means of a linear filter, we obtained 145 high-quality receiver functions (standard error below 30%) with the time domain deconvolution approach. The traces were migrated from time to depth with common conversion point stacking (CCP), using a custom earth model to account for the superficial layer of low-velocity sediments imaged by previous active source experiments. The CCP cross-sections show that the oceanic crust in the center of the gulf starts dipping toward the East at the Horseshoe Fault with an angle of approximately 15º and reaching 40 km depth below the easternmost OBS, located on top of the accretionary prism. The oceanic lithosphere-asthenosphere boundary (LAB) is also clearly seen in a West-East CCP section, with the lithosphere maintaining a constant 110–120 km thickness and following the same eastward deepening trend as the oceanic Moho. The transition from the continental to oceanic domain has also been imaged in a North-South cross-section, with some OBS stations displaying transitional crust about 15–20 km thick.

## AS25-1070

# Mapping mesoscale Eddies and Internal Tides using Distributed Acoustic Sensing in the GeoLab fibre, Madeira Island

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Internal tides are vertical oscillations of stratified ocean layers, while mesoscale eddies are large (50–300 km wide) swirling anomalies of temperature and salinity, extending from the surface to the deep ocean. Both are found throughout the ocean, often forming due to meandering currents, seafloor interactions, or water flow past islands. While surface tracking via satellites and discrete measurements from static moorings or ship-based surveys are routine, the vertical structure and subsurface dynamics of these features remain poorly understood. Their role in ocean mixing underscores the need for advanced observational techniques.

Distributed Acoustic Sensing (DAS) offers high resolution apparent strain measurements along fibre optic cables, and a unique seafloor vantage point, revealing fine-scale details of vertical structure and deep-ocean interactions. This opens new pathways for studying previously inaccessible submesoscale and mesoscale ocean dynamics.

Φ-OTDR methods are cross-sensitive to strain, temperature and pressure, and completely isolating these effects requires supplementary sensors. By calculating the SNR across 30-minute windows, we can separate and visualise the temperature contribution.

Tracking SNR variations allows us to follow temperature changes and map internal tides as they interact with the island slope and to monitor the diffusion and dissipation of mesoscale eddies in the deep basin south of Madeira Island. Both internal tides and eddies exhibit a semidiurnal tide imprint and a strong influence from the seafloor. Multiple internal tides are visible. One eddie is tracked for three days.

This work was supported by ARDITI and FCT I.P./MCTES (PIDDAC) - UID/50019/2025, LA/P/068/2020, the MODAS project (2022.02359.PTDC), and the EC project SUBMERSE (HORIZON-INFRA-2022-TECH-01-101095055).

## AS25-1074

# Preliminary observations of baleen whales on the the GeoLab fibre in Madeira, Portugal

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Baleen whales produce several sounds in the 18–100 Hz frequency range, used in reproductive, feeding and socializing contexts. These vocalizations allow detecting multiple species, assess temporal variability in song patterns, track whale movements, understand behavioural responses to sound, and estimate animal density. However, monitoring baleen whales is costly due to their extensive distribution ranges that can span entire ocean basins. Therefore, repurposing data collected by instruments originally deployed for different applications provides a practical and cost-effective solution. Distributed Acoustic Sensing (DAS) continuously records precise, broadband strain changes along the entire length of optical fibre cables, effectively converting them into dense sensor arrays. Initially employed for seismic data collection, DAS has also been successfully used for the passive detection and tracking of marine mammals and ships across over tens of km. The GeoLab fibre, exclusively dedicated to scientific research, extends ~56 km from Madeira's southern coast into the deep ocean basin. In this study, using data from the GeoLab fibre, we: 1) document the diversity of baleen whale calls recorded, and 2) assess their spatio-temporal occurrence patterns. Several types of downsweep vocalizations attributed to fin, blue and Sei whales were detected. Analysis of these sounds indicates the potential for localizing individual whales. This work further demonstrates the capability of DAS for the monitoring baleen whales through their low frequency calls. This work is supported by the Portuguese Fundação para a Ciência e Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) UID/50019/2025 and LA/P/0068/2020 https://doi.org/10.54499/LA/P/0068/2020 and by the European Union (SUBMERSE, GA 101095055).

## AS25-1081

# Lithospheric structures of the Mendocino Fracture Zone revealed by marine magnetotelluric imaging

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Seafloor fracture zones are inactive extensions of transform faults that create discontinuities in seafloor age, temperature, and bathymetry, offering key insights into lithospheric evolution. The age contrast across a fracture zone induces differential subsidence, causing lithospheric flexure, with uplift on the younger side and subsidence on the older side. However, whether fracture zones are significantly weaker than the surrounding lithosphere remains debated. Some models suggest that sharp thermal contrasts may drive small-scale convection beneath them. To investigate these dynamics, a magnetotelluric (MT) survey was conducted over the Mendocino Fracture Zone (MFZ) in 2018, approximately 600 km off the U.S. west coast. The study aimed to determine whether resistivity variations across the MFZ are primarily driven by temperature differences or other factors at the lithosphere-asthenosphere boundary (LAB). The MFZ has a strong crustal age contrast: the northern side (6.5 Ma), formed at the Gorda Ridge, is ~3 km deep, while the southern side (33 Ma), part of the Pacific Plate, is ~4 km deep. Seamounts on both sides suggest off-axis magma upwelling. A two-dimensional (2D) resistivity model from MT inversion (RMS error: 1.8, error floor: 5%) revealed strong resistivity contrasts at 30–80 km depth, likely due to temperature differences and partial melt. Additionally, shallow conductive anomalies, particularly near the southern end of the MT profile, correlate with seamounts, indicating partial melts driven by magma upwelling.

## AS25-1098

# Observing DAS strain data as proxies for oceanographic variables in the Atlantic

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Pressure signals from ocean surface gravity waves influence recordings of marine Distributed Acoustic Sensing (DAS) at shallow depths close to the coast, with the signal amplitude and period being interpreted as a proxy for the sea state. Significant wave height, wave direction, ocean currents in relation to the cable, as well as tidal information can be evaluated continuously, while the setup resembles a dense sampling array. Measurements can be calibrated with existing buoy or wave model data to extract quantitative information.

In October 2023, the GeoLab dark fibre off Madeira Island was fitted with a DAS interrogator by ARDITI and the Oceanic Observatory of Madeira. The experiment is linked to the SUBMERSE project that aims to establish continuous DAS monitoring along submarine fibre-optic cables at multiple European locations.

We use two recordings (7 days in 2023; 5 days in 2024) to show temporal variations in the DAS data close to the shore. The *f-k* spectra show the effects of varying sea states on the dispersion curves. Tides and significant wave height correlate with amplitudes of land- and seaward direction waves, and current and wave direction measurements can be estimated from the shapes of the dispersion curves.

This contributes to GEMMA (DOI:10.54499/PTDC/CTA-GEO/2083/2021). It is funded by Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) UID/50019/2025 and LA/P/0068/2020 (DOI:10.54499/LA/P/0068/2020) and by project SUBMERSE, HORIZON-INFRA-2022-TECH-01-101095055.

## AS25-1258

# Exploring the North Atlantic lithosphere: early results from the Project SEA-SEIS

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The North Atlantic Igneous Province (NAIP), which began emplacing ~62 Ma, spans a vast region from Baffin Island and western Greenland in the west to Britain and Ireland in the east. The origin of this simultaneous and voluminous volcanism, with magmatic centers scattered across the large province, remains enigmatic and continues to fuel intense debate.

Explaining this broadly distributed volcanism, along with other key questions regarding the dynamics and evolution of the Iceland plume and the North Atlantic lithosphere, has been a scientific challenge for long time, largely due to gaps in seismic data coverage. Recently, new seismic data from onshore Britain and Ireland have provided new insights, establishing strong connections between volcanism, uplift, seismicity, lithospheric depth, and thermal structure. However, these findings have remained confined to region of Britain and Ireland, due to absence—until recently—of ocean-bottom seismometers in the North Atlantic Ocean.

Here, we extend this research by utilizing offshore broadband data from ocean-bottom seismometers (OBS) deployed in the SEA-SEIS project (Structure, Evolution, and Seismicity of the Irish Offshore). Project SEA-SEIS deployed 18 OBS in the northeast Atlantic Ocean, between Ireland and Britain in the east and Iceland and the Mid-Atlantic Ridge in the northwest. The 3-component, broadband instruments, each with an additional broadband hydrophone, were deployed for 19 months, from September-October, 2018, to April-May, 2020. This dataset allows us to advance our understanding of the structure and dynamics of the North Atlantic lithosphere and underlying mantle, and will contribute to answer the long-standing questions on the origins of the NAIP.

## J04 Data assimilation and Machine Learning: Challenges and Leveraging New Opportunities

### AS25-0008

# Application of the data assimilation and AI/ML to enhance our understanding and prediction of solar activity

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Solar activity manifestations are often linked to space weather disturbances, significantly impacting human navigation, communication systems, space near-Earth activities, and exploration. Therefore, understanding how the Sun operates, initiates, and drives a variety of observed phenomena associated with its magnetic activity is crucial for transforming scientific knowledge into our predictive capabilities to mitigate its influence. A dramatic increase in the data flow from space and ground instruments and computational resources stimulates the development of high-fidelity realistic modeling and comprehensive analysis of multi-dimensional data sets. The talk will cover aspects of coupling numerical, theoretical, and observational studies through data assimilation and ML/AI to improve our understanding and tracking of the evolution of solar dynamics on global and local scales, on the example of solar cycle variation, the emergence of active regions, eruptive dynamics, and Solar Energetic Particle events. Advances and challenges in predicting solar activity on various time scales, from short (hours) to long (years), using data assimilation and machine learning approaches will be discussed.

## AS25-0197

# Better global neutral density specification and forecast through data assimilation

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Global neutral density specification and forecast are critical for satellite and debris positioning. More accurate neutral density specification can lower satellite fuel consumption and help prevent the Kessler Syndrome. Unfortunately, neutral density measurements are difficult to make, limited in number and coverage, and usually accompanied by large uncertainties. An option for improving real-time global neutral density specification is to assimilate a variety of measurements into a physics based numerical model of the Thermosphere Ionosphere. Using the Thermosphere Ionosphere Data Assimilation (TIDA) package, we investigate whether it is possible to improve global thermosphere neutral density results by assimilating GRACE-FO neutral density, GOLD TDISK neutral temperature, GOLD ON2 neutral composition, and COSMIC-2 SlantTEC measurements into the Coupled Thermosphere Ionosphere Plasmasphere with Electrodynamics (CTIPe) model. We test for improvement through a comparison with SWARM A and C neutral density.

## AS25-0199

# Seismic Hazard Analysis of the Central and Southern Segment of the Tanlu Fault Zone in China

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The Tanlu Fault Zone (TFZ) is a large-scale NNE-trending tectonic belt in eastern China, in this study, the completeness of seismic data in the central and southern segments of the TFZ was assessed and multi-parameter seismic data assimilation along with statistical learning techniques were applied to predict potential future seismogenic zones. First, the study area was divided into northern and southern subregions. Seven dominant seismic parameters were selected, including the *b*-value, seismic frequency, seismic gap, $\eta$-value, fractal dimension (*D*-value), magnitude of completeness (*M*f-value), and recurrence interval ratio (*R*m-value). The seismic events with $ML \geq 2.0$ since 1980 was processed by removing aftershocks and earthquake swarms. A uniform data assimilation framework was applied, using a time window of one year with a time step of one month, and a spatial window of 2° × 2° with a step size of 0.2° × 0.2°. This process yielded long-term, monthly-updated datasets of each seismic parameter. Next, the distribution of parameter ranges and the corresponding probability of earthquake occurrence were analyzed to construct a robust studying dataset for predicting the probability of mid-strong earthquakes within a given timeframe. Notably, the predicted high-risk zone for May 2024 corresponded to the actual occurrence of the *M*4.7 earthquake in Feidong, Anhui, on September 18, 2024. Furthermore, the potential of deep learning techniques by integrating the probabilistic sequences of multi-parameter seismic data assimilation into an improved Long Short-Term Memory (LSTM) network was explored. This approach was used to train the model and forecast future seismic hazard.

## AS25-0258

# Optimizing equatorial plasma bubble detection in all-sky images using a bootstrapping convolutional neural network

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Equatorial plasma bubbles (EPBs) disrupt satellite-based communication and navigation systems, particularly in equatorial regions. Reliable detection and classification of EPBs from All-Sky Imager (ASI) images are crucial for accurate space weather monitoring and forecasting. This study introduces a bootstrapping convolutional neural network (CNN) approach to optimize automated EPB detection, addressing challenges related to image variability and imbalanced datasets. We trained our CNN models using ASI images from the Optical Mesosphere Thermosphere Imagers (OMTI) system, deployed at the Space Environment Research Laboratory, National Space Research and Development Agency, Abuja, covering the period 2015–2020. The images were labelled/classified in three categories: EPB, Noisy/Cloudy, and No EPB, with 3000 images per category. We developed three sub-models, each trained on a separate subset of data, and combined their predictions using ensemble techniques. The individual sub-models achieved accuracies of 98.67%, 98.33%, and 95.83% on a reserved test set of 600 images. Ensemble models further improved classification accuracy to 99.17% (mean probability method) and 99.33% (mode classification method). Our results demonstrate that the bootstrapping CNN technique significantly enhances EPB detection accuracy, offering a robust tool for real-time space weather monitoring. This approach has important implications for improving the operational reliability of satellite-based navigation and communication in the equatorial region.

## AS25-0298

# Geomagnetic Field Reanalysis and Forecast Using the Ensemble Kalman Smoother

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Data assimilation techniques are powerful tools for integrating geomagnetic observational data into numerical geodynamo models, enabling the extraction of dynamic information about Earth's liquid outer core and its association with geomagnetic field variations. This study implements an extension of the ensemble Kalman filter (EnKF)—the ensemble Kalman smoother (EnKS)—and conducts synthetic data experiments to compare the performance of the two methods. The results demonstrate that, compared to EnKF, EnKS provides reanalysis results that are closer to the reference model, with improvements observed in the poloidal and toroidal components of both the magnetic and velocity fields at various depths. However, at the end of the assimilation period, both EnKS and EnKF yield identical results, indicating that EnKS does not enhance geomagnetic field predictions. To address this limitation, the study proposes a backward-secondary assimilation method, which performs a second EnKS based on the reanalysis results to improve geomagnetic field forecasts. Applying this method to the COV-OBS.x2 geomagnetic model, and incorporating data from the Swarm and MSS-1 satellites for forecasting, the results show that secondary assimilation reduces observational errors and improves short-term predictions compared to EnKF.

## AS25-0338

# Machine Learning Applied in Geophysical Time Series to Recover Data Missing – The MALERD Applicative

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The issue of partial missing geophysical data is a significant problem in sophisticated analyses due to the introduction of bias which can compromise the quality of resultant analyses. In addressing this challenge, various statistical methodologies have been employed to supplement the incomplete data. However, it should be noted that these methods (such as ARIMA) are not optimally suited to non-stationary time series. Furthermore, these methods necessitate manual intervention in certain statistical parameters. Consequently, machine learning (ML) emerges as a methodology that can effectively address the complex behavior inherent in time series. The present work introduces an algorithm capable of identifying various issues within a time series, including dropped, spikes and missing data. To this end, Ridge Regression and Fourier analyses were employed to develop the MALERD (Machine Learning Recovery Data) application, which is capable of identifying anomalous values, analyzing the dominant frequencies of the time series and estimating data gaps with high precision. The results obtained are consistent with the statistical parameters obtained with the time series used to train the ML.

## AS25-0374

# Instrumental bias with ruin your data assimilation

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The goal of data assimilation is to combine both models and observations to produce a representation of a complex system which is better than either separately. Most data assimilation techniques can be thought of as a statistical method to weight the contribution from observations and the contribution from models based on their respective errors. These techniques generally assume that the errors are due to some noise process, and have zero mean. There is little study of what occurs if this zero-mean assumption is violated. This presentation will show the outcome of an ionospheric data assimilation experiment where several international calibration standards are compared, and all are shown to have significant systematic errors. These improper calibrations cause errors in reconstructed electron density of over 100%, when compared to in-situ measurements. This can be addressed by including instrument calibration self-consistently in the data assimilation state.

## AS25-0383

# An explainable machine learning model for large-scale travelling ionospheric disturbances forecasting

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Travelling Ionospheric Disturbances (TIDs) are wave-like plasma density fluctuations that ripple through the ionosphere. Large-scale TIDs (LSTIDs) typically originate from energy injections in the polar regions, driven by Joule heating, Lorentz forces and particle precipitation. These disturbances can disrupt Global Navigation Satellite Systems (GNSS) and radio communications, especially at mid-latitudes, making their detection and forecasting critical.

Since there are no physical or empirical models to forecast LSTIDs, within the EU-funded T-FORS project we developed a Machine Learning model – based on CatBoost, a framework for gradient boosting on decision trees – to forecast LSTID occurrences within 3 hours before their onset. The model uses a catalogue of manually inspected HF-based LSTID detections along with various external drivers as inputs, spanning 9 years (2014–2022) and including auroral electrojet indices, solar wind data, ring current index, solar zenith angle and data from the European network ionosondes.

To enhance interpretability and explainability, we use the SHapley Additive exPlanations (SHAP) framework to link the model's predictions to the underlying physical drivers. Our results show an improvement of 72–93% compared to a rule-based benchmark.

We address probabilistic forecasting from a cost-sensitive learning perspective and uncertainty quantification for end-user risk management, using the conformal prediction framework. We also discuss the steps towards the (currently underway) operational deployment of the model in a near real-time setting.

## AS25-0384

# Using Physics Informed Neural Networks for Local Flow Estimations of the Earth's Core (Or0ltbAOK64EWASUhfYnbYYtv05A)

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Recent advancements in machine learning enable new approaches to studying the dynamics of the Earth's core. This work introduces a novel approach that leverages Physics-Informed Neural Networks (PINNs) to perform local flow inversions at the core-mantle boundary. The Earth's geomagnetic field is generated by the motion of liquid iron in the outer core, and by assuming that changes in the magnetic field are advection-dominated, we can relate fluid motion at the core surface to geomagnetic field variations. Traditionally, core flow models are represented using a global basis such as spherical harmonics, but here we show a regional approach in order to study local flow features.

We present our approach to perform local flow inversions at the core-mantle boundary using PINNs. We minimise a loss function that combines both data loss, which measures the fit to the magnetic field variations, and a physics-based loss, which ensures adherence to dynamical conditions assumed to govern the flow, necessary to produce unique flow solutions. We highlight the key setup and parameter choices necessary for this methodology and demonstrate its flexibility in accommodating different dynamical conditions. Our methodology does not suffer from leakage between regions, and we reproduce flow features seen in other global studies, such as the anticyclonic planetary gyre, showing that this is a data-driven feature which is not reliant on the details of any specific inversion method. Finally, we explore potential use cases for this technique, applicable not only to Earth's outer core but also to similar scenarios on other planets.

## AS25-0422

# Variation of the polar ionosphere reproduced by data assimilation into an emulator of a magnetosphere-ionosphere model

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In order to reproduce the dynamic behavior of the polar ionosphere with data assimilation, it is essential to compare observational data with the numerous results of global magnetohydrodynamic (MHD) simulations. However, since each MHD simulation run requires a huge amount of simulation time, it is extremely difficult to obtain a sufficient number of the results for data assimilation. We have developed a machine-learning-based emulator of an MHD model of the magnetosphere to efficiently obtain the temporal evolution of the polar ionosphere. This emulator provides an empirical prediction of the ionospheric variation as a result of the magnetospheric response to the solar wind variation. We then incorporate the SuperDARN data into the emulator to improve the realism of the prediction. Data assimilation of the line-of-sight velocity data by the SuperDARN radars is conducted by an algorithm which combines the ensemble transform Kalman filter with the importance sampling method to consider non-Gaussian features of the SuperDARN data. We compare the polar cap potential drop derived from the the estimated potential distribution with some geomagnetic indices. The result suggests some correspondences in variations between the polar cap potential drop and geomagnetic activity.

## AS25-0431

# Hybrid Method of Data Assimilation with Preliminary Estimated Fault Model as a Tsunami Forecast for Future Nankai Trough Earthquakes

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The dense pressure station networks were installed along the Pacific side of Japan to detect early tsunamis and predict tsunamis along the coast. A tsunami forecasting method using tsunami data assimilation can be implemented because real-time pressure data from dense sensors are available. However, pressure data near the source area may include unusual steps due to the response to strong seismic motion from earthquakes. If pressure data observed outside a source region are used for the data assimilation procedure, it takes too long to capture the tsunami propagation field for early warning. We developed a hybrid method integrating a tsunami data assimilation procedure with preliminary fault model estimation. In this approach, pressure sensors above the main source area are excluded, and a preliminary fault model is used to generate the tsunami wavefield.

We tested the effectiveness of the hybrid method of tsunami data assimilation with a preliminary fault model for the great Nankai Trough earthquake case. The fault model of the great Ansei earthquake estimated by Furumura et al. (2021) was used as a reference or synthetic model. To assess the effectiveness of the hybrid method, we compared the synthetic and forecasted tsunami waveforms at several coastal stations of Tosashimizu, Kochi, Muroto, Shirahama, and Nobeoka. The results showed that with an appropriate preliminary fault model, the accuracy of the forecasted waveforms improved as the data assimilation time window increased. The results indicate that the forecasting performance of the hybrid method can be improved by increasing the data assimilation time window.

## AS25-0437

# Enhancing automated earthquake detection with deep learning: application to ocean-bottom seismographs using automated labeling and transfer learning

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We aim to enhance deep learning for earthquake detection using ocean-bottom seismographs (OBS). Previous studies have developed EQTransformer, a deep learning-based seismic waveform detection tool capable of automatically identifying P and S waves, and GaMMA, a machine learning-based earthquake association model that links seismic arrivals from different stations to the same event. While these tools perform well on land, they face challenges with OBS data due to marine noise and complex horizontal waveforms. To address these limitations, OBSTransformer was introduced, leveraging transfer learning to adapt EQTransformer to OBS data.

In this study, we utilize OBSs deployed in mid-Okinawa trough (NOT Array), consisting of 30 Taiwan-developed BBOBS units. We compare EQTransformer+GaMMA versus OBSTransformer+GaMMA against the Japan Meteorological Agency (JMA) catalog. For one day (UTC 2019/02/01) in the region between 26°–32° N and 127°–132° E, JMA detected 31 earthquakes. OBSTransformer identified 13 events (3 matching JMA) , while EQTransformer detected 378 events (7 matching JMA). Both models show limited overlap with the JMA catalog, but OBSTransformer demonstrates higher precision in identifying actual seismic events. Analysis reveals EQTransformer struggles with larger earthquakes, while OBSTransformer has difficulty with smaller events.

Given variations in OBS instruments, we aim to enhance model generalization through automated labeling and transfer learning. This reduces manual annotation while improving adaptability across different instruments without extensive computational resources. Our approach enables better seismic monitoring, improved location accuracy through enhanced coverage by OBS deployment, and more effective microseismic detection.

## AS25-0524

# Utilising data assimilation to study the impact of geodynamo priors and geomagnetic data on inverted core surface flows

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High quality continuous satellite magnetic data gives unprecedented insights into core surface motions, but the inversion process remains under-determined, thus requiring additional information. Data-assimilation techniques like the pygeodyn inversion tool can forecast core surface dynamics using stochastic equations anchored to prior geodynamo information. However, there is no clear overview of the relative importance of different factors entering in the pygeodyn core flow inversion. We document the impact of: (1) choice of geodynamo prior, (2) choice of geomagnetic field model (CHAOS-7, COV-OBS.x2 and Kalmag), and (3) choice of maximum spherical harmonic degree for secular variation. Six dynamo priors allow us to analyse the influence of changing the input parameters towards Earth-like values and changing the dynamo set-up.

We quantitatively show that changing the prior has a greater impact on the core surface flow than the choice of magnetic field model used as observations. This difference becomes less pronounced in the past due to the data quality decreasing and the field models showing more divergence. Furthermore, we find that the slowly evolving 'background' component of flow is more variable among models than the transient component. Transient flow motions appear very coherent for all considered dynamo priors and field models. Finally, we quantify the efficiency of core flows for generating magnetic variations as a function of frequency. Normalized to their magnitude, rapid changes generate relatively more magnetic signal than slow variations. Consequently, a larger part of core surface motions enters the null space of the kinematic core flow inverse problem towards long timescales.

## AS25-0606

# Relating subduction parameters to the spectrum of slow to fast earthquakes using machine learning on a global scale

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Moment magnitude ($M_w$) is widely used to estimate earthquake size, as it effectively quantifies rupture extent, being also useful for tsunami hazard. In contrast, energy magnitude ($M_e$) better characterizes potential damage from strong ground motion, making it more relevant for seismic hazard assessment. In this study, we use a catalog of subduction interface earthquakes containing both $M_w$ and $M_e$. We quantify their differences and examine their relationship with subduction parameters along global megathrusts to identify potential links to fast ($M_e > M_w$) or slow ($M_w > M_e$) events. Additionally, we consider a catalog of slow-slip events (SSEs), characterized by $M_e \approx 0$ and commonly occurring in subduction margins, to complement the database and investigate the characteristics of regions prone to slow-slip behavior. Using a parametric approach, we applied statistical analysis and machine learning (ML) algorithms to predict regions in which fast or slow-slip dominates, modeling it as a nonlinear function of subduction variables. We then employed Shapley Additive exPlanations (SHAP) on the ML outcomes, to identify the most influential factors associated. Preliminary analysis and previous studies suggest the possibility that frictional properties of the subducting plate and the variability along the strike of the trench, which influence plate coupling and stress levels, may play a key role to induce fast or slow-slip on the interface. Our results provide valuable insights into the complex, nonlinear processes related to the spectrum of slow to fast earthquakes on a global scale and highlights regions where previously undetected SSEs may be occurring.

## AS25-0759

# PGVnet: A Machine Learning Framework for the Generation of Rapid, Physics-Consistent PGV Maps

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The rapid and accurate estimation of ground shaking intensities is essential for seismic hazard assessment and near-real-time disaster response. Although empirical ground motion models enable fast intensity predictions, they simplify the underlying physics and often exhibit large variability. Conversely, physics-based simulations—although highly accurate—are computationally expensive, making them impractical for large-scale hazard assessments.

To overcome these limitations, we introduce a novel two-step machine-learning framework that predicts peak ground velocity (PGV) for arbitrary seismic sources within a defined domain, combining the accuracy of physics-based models with near-instantaneous inference. In the first step, an ensemble of XGBoost predictors, trained on a "reciprocal" Green's function database, generates a sparsely sampled PGV map for a given source. In the second step, this coarse map is refined into a continuous spatial prediction. By leveraging Green's function reciprocity, our approach markedly reduces the required number of simulations in training, lowering both computational and storage demands. Our framework provides continuous, grid-free PGV predictions at any scale and inherently accounts for complex 3D geological and topographic effects on wave propagation. It can deliver results within seconds while maintaining accuracy up to the highest frequency captured in the physics-based simulations. This makes PGVnet ideal for near-real-time applications such as rapid earthquake response, as well as large-scale probabilistic seismic hazard analyses. Validated in the geologically-complex San Francisco Bay Area, our approach generates PGV maps consistent with physics-based simulations, offering an effective balance between computational speed and accuracy.

## AS25-0799

# Advancing Earthquake Forecasting with Neural Point Processes

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The use of probabilistic short-term earthquake forecasting by government agencies worldwide is the result of the successful development of self-exciting point process models such as the Epidemic-Type Aftershock Sequence (ETAS) model. Although these models have shown strong performance in prospective forecasting experiments conducted by the Collaboratory for the Study of Earthquake Predictability (CSEP) across diverse tectonic settings, they are many known modeling inaccuracies due to their restricted parametric form. Recently, Neural Point Processes (NPPs) have emerged as a machine learning alternative, promising greater flexibility and significantly improved computational efficiency. While early applications of NPPs to earthquake forecasting have demonstrated advantages, rigorous evaluation and development is needed to fully realize the potential of this new class of model. In this talk I will present initial benchmarking results from various regions around the world, including EarthquakeNPP, a benchmarking platform to facilitate this. I will highlight both the immediate advantages of NPPs and ongoing efforts to address domain-specific challenges in earthquake forecasting. I will argue that overcoming these challenges requires active collaboration between machine learning and seismology communities, supported by transparent and rigorous model evaluation.

## AS25-0814

# Analysis of the dipolar geomagnetic field over the historical period using machine learning-based predictions

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The geomagnetic field can be mathematically represented through spherical harmonic expansion, enabling the development of field models that describe its main features. The coefficient g_1^0 represents a geocentric axial dipole and is the primary component of these models. For periods before 1840 CE, discrepancies among models arise due to spatial and temporal data heterogeneities and differences in coefficient fitting techniques. Given these discrepancies for the period 1500–2020 CE, this study aimed to achieve convergence in the adjustment of g_1^0 across different models. A machine learning (ML) approach was applied using the variational Gaussian process (VarGP) to predict a time series of g_1^0 for the historical period. The input data consisted of selected g_1^0 coefficients from different models, with varying weights assigned based on data reliability. Results show that the ML-derived g_1^0 (VarGP model) exhibits a variation of approximately 2.5% within the 95% confidence interval, demonstrating a good fit, especially with historical models. Model validation was performed using geomagnetic observatory and archeomagnetic data, showing that observatory records fell within the model's uncertainty margins. The validation indicates that the VarGP model effectively captures both dipolar and non-dipolar field characteristics after coefficient adjustments.

## AS25-0831

# The JAGUAR-DAS whole neutral atmosphere reanalysis: JAWARA

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Using the Japanese Atmospheric General circulation model for the Upper Atmosphere Research-Data Assimilation System (JAGUAR-DAS), a whole neutral atmosphere reanalysis dataset (JAWARA) over about 19 years from September 2004 to December 2023 is produced. JAWARA is the first long-period reanalysis covering the height region from the surface to the lower thermosphere (~ 110 km). This wide height coverage is a notable advantage over other operational reanalysis datasets, which cover up to the middle mesosphere.

Key dynamical characteristics are compared between JAWARA and two satellite observations and three other operational reanalysis datasets in their covered height regions. The seasonal variations of zonal mean temperature and zonal wind are similar between JAWARA and the datasets used for comparison. The climatologies of zonal mean temperature, zonal wind, residual-mean circulation, and E-P flux in the meridional cross section are also broadly consistent with other reanalysis datasets. The analyzed residual-mean vertical flow in the northern high latitudes in the middle atmosphere exhibits the well-known patterns of upwelling in summer and downwelling in winter. JAWARA also shows a prominent feature of strong downward propagating anomalies from the lower thermosphere to the upper stratosphere after sudden stratospheric warmings.

This analysis takes full advantage of the JAWARA data, which cannot be made using satellite observations and other reanalysis datasets. This reanalysis product is expected to contribute broadly to future research on the characteristics of observed mesospheric phenomena, thermosphere–ionosphere coupling, space weather, and improvement of middle atmospheric meteorological systems, including their interannual and decadal scale variability.

JAWARA is available online: https://doi.org/10.17592/002.2025010407.

## AS25-1068

# Cut-off threshold setting bias in deep learning picks classification, insights from a combined land and OBS dataset

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The quality of earthquake catalogs is strongly influenced by event location accuracy, which depends not only on precise phase onset picking but also on the number and quality of detected phases and station coverage. In machine learning classification tasks, the F1-score is commonly used to balance false positives and false negatives. However, in seismic phase classification, this practice has often been overlooked due to the sensitivity of model performance. The selection of classification thresholds for seismic phase picks significantly impacts event association and overall catalog quality. In this experiment, we analyzed raw waveforms from land and ocean-bottom seismometer (OBS) stations, covering the Azores-Madeira-Canary Islands region, for six known events with small to moderate magnitudes. EQTransformer for land data and PickBlue for OBS data was applied to investigate the effects of pick classification thresholds on event association. Five different P- and S-pick classification threshold pairs were tested, to evaluate precision, recall, and F1-score for each. The results were compared to manually picked phases from the same events to assess the impact of threshold variation on catalog consistency. Preliminary results suggest that threshold pairs of 0.1/0.1 for land data and 0.1/0.01 for OBS data provide the optimal cut-off values. These values will be applied to the entire dataset for production of earthquake catalog along the Terceira Rift.

## AS25-1118

# Machine Learning for Ionograms Parameter Extraction: A Time-Series Approach to Ionospheric Monitoring

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To investigate and determine the state of the ionosphere, ionograms are used and it is obtained from ionosondes. In this work, we analyze ionograms obtained from VIPIR ionosondes, part of the Low-Latitude Ionospheric Sensor Network (LISN). Over the past decades, various tools have been developed for the extraction of ionospheric parameters with ionograms, for example: ARTIST-5 and among others. There are some approximations in previous works using deep learning for automatic scaling with parameters extraction of great importance for the identification of the E and F2 layers, as well as the occurrence of the maximum frequency in the F2 layer (foF2) and the height at which it occurs (hmF2). These tools generally work accurately for relatively quiet days (QD), but not for days with irregularities in the F layer (i.e. spread-F). Where a lot of variability is observed in the parameters obtained on those days and traditional manual correction is necessary. In this work, we trained a model combining Convolutional Neuronal Network (CNN), Long Short-Term Memory (LSTM) and Dense layers that can capture the short-term variability of the ionosphere and our trained model returns the frequency profile values. We tested and compared the frequency profiles from our model with manual scaling and parameters obtained with ARTIST 5.0 showing significant differences.

## AS25-1126

# Seismicity and Fault Structure of the Western Churchill Province: Insights from Machine Learning-Based Earthquake Relocation and Cluster Pattern Analysis

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The Western Churchill Province (WCP), a component of the Canadian Shield, is a geologically complex region characterized by a history of seismic activity. Despite its seismic history, the seismicity and associated fault structures within the WCP remain largely unexplored. This study seeks to enhance our understanding of the seismic behavior of the WCP by analyzing earthquake data using EQTransformer for preprocessing and event relocation with a machine learning algorithm. Subsequently, Adaptive DBSCAN clustering is employed to investigate spatial and temporal patterns in the seismicity, providing insights into active fault systems and their relationship to regional tectonics. The relocated seismic events reveal critical information regarding the distribution, depth, and frequency of seismic activity within the region. By applying Adaptive DBSCAN, we identify clusters of seismic events that may correspond to fault zones or other structural features, illuminating potential active fault structures in the area. This methodology offers a novel approach for identifying patterns in the seismicity of the WCP, contributing to the comprehension of fault dynamics and seismic hazard assessment in this geologically significant region. Our findings will serve as valuable input for future seismic hazard assessments and are anticipated to advance the understanding of fault systems within the Western Churchill Province.

## AS25-1134

# Dynamics of tens-of-keV electrons in the inner magnetosphere in machine learning, physics-based and data assimilation models

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Earth's radiation belts and ring current, filled with energetic electrons, pose a significant threat to satellite operations. In particular, the tens-of-keV electrons in the inner magnetosphere can accumulate at the surface of the satellites leading to surface charging, and therefore need to be carefully monitored. Their dynamics, however, are considered particularly challenging to predict, as electrons at these energies can be injected from the tail on minute timescales, with their fluxes exhibiting fast and unpredictable changes by orders of magnitude. Here, we present an update of the Medium Energy electRon fLux In the outer radiatioN belt (MERLIN) model, based on a full solar cycle worth of observations by the Van Allen Probes and Arase missions. We show that machine learning models can reproduce the dynamics of this challenging population with a very high accuracy, capturing small features such as the magnetic local time (MLT) asymmetries in electron flux distributions. Additionally, we demonstrate comparisons of the model predictions with the 4D physics-based Versatile Electron Radiation Belt (VERB) code, as well as data assimilation results. We discuss the differences and similarities in physical features reproduced by the three approaches and highlight the requirements for real-time monitoring of the tens-of-keV electron populations.

## AS25-1162

# Development of adjoint-based data assimilation method toward predicting SSE evolution: Two-step optimization of frictional parameters and initial strength on faults

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Data assimilation (DA) has tried to incorporate GNSS data into physics-based fault slip models to estimate frictional properties and predict future slip evolution on faults. For unstable slip events such as ordinary fast-slip earthquakes and slow slip events (SSEs), the accurately estimation ofng both the time-varying frictional strength, as well as and the time-invariant frictional parameters, is crucial for reliable slip prediction. However, because the frictional strength has not been directly observed, and thus, previous DA studies that estimatedestimating the frictional parameters often assumed a steady-state strength at the initial time of estimationassimilation, which limitedlimits the accuracy of long-term slip prediction. In the present study, we propose a new adjoint-based DA method that estimates an appropriate initial frictional strength along with the frictional parameters to for assimilateing long-term SSEs. The key idea is to impose an additional constraint on DA that assuminges that the current SSE will recurs periodically, though the exact interval is unknown. This approach reflects the observed recurring nature of SSEs. This new method is validated through numerical experiments focusing on long-term Bungo Channel SSEs in southwest Japan. The results demonstrate that our proposed method provides reasonable estimates for both the initial strength and the frictional parameters, enabling accurate predictions of slip evolution and the timing of subsequent SSEs, along with determining estimating the unknown recurrence interval. The method proves effective even with data windows shorter than the recurrence interval, overcoming the limitations of previous DA methods.

## AS25-1202

# Probabilistic fusion of seismic velocity models using Gaussian processes

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Seismic velocity models—estimates of the Earth's seismic wave speeds—underpin earthquake ground motion prediction in physics-based seismic hazard analysis, serving as key inputs to wave equation solvers. They continue to be produced at varying resolutions and scales, stemming from diverse inverse methods and direct observations. Owing to the inherent non-uniqueness of the seismic inverse problem and the numerous techniques for estimating seismic velocities, many velocity models exist for a given region. Consequently, the choice of which velocity model to use in ground motion prediction is often subjective. This choice significantly impacts the results, as different models have varying structures, length scales, and amplitudes. Current seismic hazard analysis methods do not account for this source of uncertainty.

We present a method for the probabilistic fusion of seismic velocity models using scalable Gaussian process (GP) regression. The method fits a probability distribution to any number of spatially overlapping velocity models. A key advantage of GPs is their ability to capture spatial correlations, enabling the sampling of realistic velocity structure realisations from the fitted distribution. We show how these samples can serve as inputs to physics-based earthquake simulations, yielding probabilistic ground motion estimates that reflect inconsistencies among existing velocity models. We also explore the impact of different velocity models on ground motion prediction, demonstrating the necessity of probabilistic methods like ours for improving uncertainty quantification in seismic hazard analysis. Although exemplified in seismic hazard, our probabilistic data fusion approach is broadly applicable across the geosciences.

## AS25-1227

# Enhancing Teleseismic P-Wave Detection and Tomography in the Groningen Area: Comparing Traditional Methods and Machine Learning

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Teleseismic P-wave arrival detection is crucial for seismic tomography but presents challenges for both traditional and machine learning (ML) methods. ML-based seismic pickers, often trained on local and regional datasets, struggle with teleseismic arrivals due to their lower frequency content and different characteristics. Moreover, ML-based seismic pickers struggle with datasets with different characteristics and noise conditions from data used for their training. In this study, we compare ML approaches with traditional techniques such as short-term average to long-term average (STA/LTA) detection, cross-correlation, and P-wave stacking on the data of the Groningen array (NL). To improve ML models for teleseismic detections, we develop a new training dataset for ML-based detection of teleseismic events using synthetic waveforms generated with AxiSEM/Instaseis. With this new training dataset, we aim to use ML to improve the picking of teleseismic P-wave of the Groningen array quantitatively and qualitatively.

We use our detected picks to generate a new tomographic model of the Groningen area with FMTomo, offering improved insight into the lithospheric velocity structure. This, in turn, provides crucial information on the deeper velocity structure of a region with significant potential for geothermal resources and CO2 and hydrogen storage activities.

## AS25-1247

# Drone-Based Segmentation of Recent Mud Extrusions in Sicilian Mud Volcanoes

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Mud volcanoes form when overpressured fluids, primarily saline water and methane, become trapped beneath impermeable layers. Their intermittent eruptions of gas and liquefied sediment pose significant geohazard risks due to their dynamic and unpredictable nature. Satellite-based approaches are commonly used for large-scale geospatial analyses, but they lack the spatial resolution needed for monitoring smaller sites. To overcome this limitation, we deployed a high-resolution Phantom 4 drone for data collection and developed a deep-learning workflow based on a U-Net architecture to identify recent mud extrusions in Sicilian sites, including Paternò, Santa Barbara, and Aragona. Our approach employs a combined loss function (binary cross-entropy + Dice), evaluated using Intersection over Union (IoU). We trained the U-Net experimenting with different optimizers (Adam, AdamW, and stochastic gradient descent), learning rates (0.001, 0.0005, 0.0001), and batch sizes (2, 4, 8, 16, 32). The best results, with IoU scores often exceeding 0.93, were achieved using smaller batch sizes (2 and 4) with Adam and AdamW optimizers. Conversely, stochastic gradient descent converged more slowly and occasionally plateaued. We attribute the success of Adam-based optimizers to their adaptive learning rates, which stabilize training on high-resolution drone imagery. Additionally, using smaller batch sizes helps mitigate overfitting and preserves fine details by increasing the number of parameter updates per epoch. Compared to traditional methods, this approach offers greater accuracy and responsiveness, which are crucial for monitoring volatile geological environments. Ultimately, this integrated workflow demonstrates how small-scale drone-based surveying and deep-learning can significantly enhance mud volcano monitoring in geographically confined areas.

## AS25-1255

# Masked graph neural network for the rapid ground motion prediction in Italy

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Rapid prediction of earthquake ground motions is a key focus in seismology. These predictions are valuable for earthquake early warning systems, post-event damage estimation and seismic hazard assessment. Here, we present an updated version of TISER-GCN (Bloemheuvel et al., 2022), a graph neural network (GCN) architecture designed to predict the maximum intensity measurements (IMs) of ground shaking from the pattern of 10 seconds long seismic waveforms starting at earthquake origin time, without prior knowledge of earthquake location, distance and magnitude. In this work, we applied the model to nearly 600 seismic stations deployed in Italy listed in the INSTANCE benchmark dataset (Michelini et al., 2021) —a significant increase in terms of number of stations and areal extension from the original TISER-GCN, which was limited to a fixed geometry with only 39 stations located in a smaller area in central Italy. The input data used in this study consist of the three-component earthquake waveforms collected in INSTANCE. To ensure high-quality training data, we adopted selection criteria to minimize signal saturation and prioritize reliable recordings. We show that applying a mask to stations where the P-wave arrives within the first 10 seconds improves model performance. Incorporating additional information further enhanced the predictive accuracy of the Masked GCN, which demonstrated lower bias while maintaining error variance comparable to the Bindi et al. (2011) ground motion model. Our findings indicate that the proposed approach provides accurate predictions of ground motions, comparable to those obtained with the original TISER-GCN, while requiring a fixed stations geometry.

## AS25-1423

# Towards Integration of Data Assimilation and State-of-the-Art Information Science Techniques for Seismology

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The STAR-E Project that aims to develop state-of-the-art information science techniques, including artificial intelligence and data assimilation, applicable in seismology is going on in Japan, supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). We introduce our various activities in the SYNTHA-Seis, which is one of the research teams in the STAR-E Project. We developed the four-dimensional variational (4DVar) method that enables uncertainty quantification (UQ) based on the second-order adjoint method (Ito et al., 2016), and showed that the optimum frictional parameters at the plate boundary and their uncertainties could be appropriately estimated by applying the proposed 4DVar method to a slow-slip model (Ito et al., 2023). On the other hand, we have been developing deep learning models to detect earthquake signals in seismic continuous waveforms, such as for phase-picking (Tokuda and Nagao, 2023; Katoh et al., in revision) and for P-wave polarity determination with UQ using the Monte Carlo dropout method (Katoh et al., submitted). We have also been developing methods to extract waveform features of low-frequency tremors (LFTs), such as a template matching technique to extract LFTs waveforms (Gerardo Mendo et al., in revision), a deep learning model to detect LFTs in historical paper records obtained by mechanical seismograms more than fifty years ago (Kaneko et al., 2023), and a deep learning technique to acquire a stochastic differential equation expression of LFTs (Kusui et al., submitted). We discuss the future direction of integration of data assimilation and cutting-edge information science techniques in seismology.

## AS25-1441

# Recurrent You Only Look Once (YOLO) Model for Solar Magnetic Tornado Detection

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Earlier we have developed an automated pipeline for detecting solar magnetic tornadoes. We define these structures as magneto-plasma objects in the solar corona where the magnetic field is twisted. Our previous work was based on a convolutional neural network (MobileNetV3 [Howardet al., 2019, ICCV]/EfficientNet [Tan Le, 2019, ICML]/EfficientNetV2 [Tan Le, 2021, ICML]) with an RNN (using LSTM or GRU layers) to classify sequences of SDO/AIA 171 Å images and a YOLOv8/11 model [Jocher et al., 2023, Ultralytics YOLO] for bounding box detection of tornadoes on the solar limb. In this study, we introduce a third approach — Recurrent YOLO. We integrate ConvLSTM or ConvGRU layers into the backbone of YOLO v11, enabling the capture of temporal dynamics of the rotating solar structure. We compare and discuss the results of all three methods, evaluating detection accuracy and recall, as well as latency. In addition, we demonstrate a machine learning inference server. The backend is powered by Python, FastAPI, Triton, Minio, Redis, and Celery, while the frontend is written with JavaScript, React, and Redux. Monitoring is performed using Prometheus, Promtail, Loki, and Grafana, with the entire infrastructure containerized via Docker. This work provides insights into the performance and accuracy of different approaches for identification of solar structures and illustrates an end-to-end solution for real-time inference and monitoring.

## J05 Interdisciplinary observations of pre-earthquake processes – from mechanical to electromagnetic and geochemical phenomena

### AS25-0059

# Is There Accelerated Crustal Deformation Before Large Earthquakes? A Case Study of Strong Intra-Plate Earthquakes in China (QMrlK1AGOGI8SA6Q34h1bM7W33vb)

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The presence of a detectable precursory phase of fault slip prior to significant earthquakes has been a topic of debate for decades. A recent study (Bletery & Nocquet, 2023) have showed that there were observed exponential acceleration of slip before large earthquakes. However, related studies (Hirose et al., 2024) did not observe the same phenomenon using tiltmeter data. Moreover, their analysis is mainly based on large earthquakes occurred on subduction zones and lacks of cases of intraplate earthquakes. Here, taking 15 strong intraplate earthquakes in China as cases, we have found that there might be no obvious deformation acceleration before those earthquakes. We have also investigated several key factors which might contribute to uncertainties of this approach. Our results indicate that the exponential acceleration phenomenon is linked to earthquake characteristics and influenced by the spatial distribution of nearby signals.

## AS25-0084

# Seismogenic structure revealed by multi-scale electromagnetic methods

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Seismogenic structure plays a fundamental role in understanding the potential risk zones of strong earthquakes. Besides the crust-scale structure, the near surface structure and the upper-middle mantle structure also contribute to the seismogenic process. Therefore, multi-scale imaging methods are required for the study on seismogenic structure. Electromagnetic method is one of the main approaches for imaging the interior structure of the earth. Due to its sensitivity to fluid, electromagnetic method has been widely adopted in the study on seismogenic structure and earthquake physics. In this study, we propose a multi-scale imaging approach by combining series of electromagnetic methods. We demonstrate that the broadband magnetotelluric (MT) array data are sensitive to the crust-scale electrical structure, and the traditional geomagnetic depth sounding (GDS) method with the long period source in magnetosphere can reveal the middle mantle structure. To fill in the imaging gap between the traditional MT and GDS methods, we have made use of the geomagnetic diurnal source in ionosphere and developed the alternative/joint inversion method of the electrical structure in the upper-middle mantle. For the near surface structure, we have developed a novel approach of high-resolution imaging by using seismoelectric signals and airborne electromagnetic data, respectively. Our study shows the potential applications for imaging the multi-scale seismogenic structure.

## AS25-0187

# Pre-slip-induced hydrological precursors

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This paper summarizes two cases of hydrological precursors and their mechanisms.

In Japan, water level recorded at a "sensitive" well during 1989–99 showed 5 pre-earthquake drops before 5 large earthquakes of magnitudes 6.1–8.1 at distances of 220–1260 km, and a large 6-month-long drop before a rare local earthquake of magnitude 5.8 about 50 km away. The high sensitivity of the well is attributed to its tapping a permeable aquifer which is connected to a nearby fault which contains a weak but impermeable fault-gouge layer under a large hydraulic-pressure gradient and in a nearly critical stress condition. The observed precursory drops are attributed to the stress increments associated with the occurrence of slow-slip events before the earthquakes.

In Taiwan, a large stream-flow increase followed by a larger decrease and a water-level change were recorded shortly before the 1999 magnitude 7.6 Chi-Chi earthquake near the epicenter on the hanging-wall side of the seismogenic thrust fault. These precursory changes are attributed to: Crustal-bulging; tensile fracturing starting at the surface trace of a secondary fault and progressing to greater depths; groundwater flowing down from the stream banks to the stream bed causing the precursory stream-flow increase, then stream water draining from the streambed to the crust below, causing the flow decrease; and occurrence of pre-earthquake slow-slip events, causing the water-level precursor and the earthquake.

Thus, hydrological and other kinds of precursors can be reliably observed and the mechanisms clearly understood, if crustal heterogeneity and the occurrences of fluid movement and slow-slip events are recognized.

## AS25-0267

# The potential impact of space weather on earthquake processes: A case study of Mw5.0 in North Tien Shan

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In recent past, territory of city Almaty (formerly Verny) suffered three times from strong earthquakes in North Tien Shan, where the largest was Kemin event of 1911 with M>8. On March 4, 2024, the Mw=5.0 occurred on area of Kemin source. It was felt in Almaty with intensity of 5 points and caused noticeable panic, since over past 34 years there were no earthquakes with M>5.

Sokolova et al. (Russian Seismological Journal, 2024, https://doi.org/10.35540/2686-7907.2024.4.01) presented instrumental and macroseismic data from March 4 earthquake and noted that it was preceded by the process of formation of ring structure from weak earthquakes, which presumably outline zones of high content of fluids in uppermost mantle (Kopnichev and Sokolova, 2010, J. Volcanology and Seismology, https://link.springer.com/article/10.1134/S0742046310060047). Recently, Ouzounov and Khachikyan (Geosciences, 2024, https://doi.org/10.3390/geosciences14060159; Remote Sens. 2024, https://doi.org/10.3390/rs16142544) showed that strong earthquakes may be preceded by geomagnetic storms, presumably activating the rise of mantle fluids, possibly with a cumulative effect, ultimately leading to earthquake occurrence. Above works led to idea of analyzing geomagnetic and solar wind data before March 4, 2024 earthquake. We found that at time interval of three months, there were three geomagnetic storms that met the criterion by Ouzounov and Khachikyan, 2024 for occurrence strong earthquakes. Namely, in time of each storm onset, high latitudinal part of longitude where latter mentioned earthquake occurred, was located under the polar cusp, where solar wind energy can freely penetrate to the atmosphere. Work was funded by Kazakhstan's CSMSHE, grant IRN-AP19677977.

## AS25-0336

# Changes in the seismic regularity coefficient preceding larger seismic events, from laboratory-scale events to giant earthquakes

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According to laboratory experiments, the final failure is preceded by the fracturing process synchronization and then the transition toward a more chaotic fracturing regime. We track these fracturing process stages with the seismic regularity coefficient, dc. For a series of earthquakes, we calculate the waiting times and epicentral offsets—the times and distances between every pair of consecutive earthquakes. We then link them to the occurrence times of the second event. After transformation to equivalent dimensions, the waiting times, epicentral offsets, and magnitudes of the second events define points in the [0,1] cube. dc is the average distance between such points. Its time variations reflect changes in the seismic process regularity. When the process is more regular, the waiting times, epicentral offsets, and magnitudes become similar, and dc decreases. Conversely, the dc increase indicates a transition toward irregularity.

We present the dc time changes for seismic processes, beginning from AE in laboratory tests, through anthropogenic seismicity, swarms, big, M7+ earthquake cases, to giant, M8+ earthquakes in subduction zones. In all cases, the major ruptures were preceded by a significant decrease and increase in dc. Such results indicate that an increased regularity and, next, the deregulation of the seismic process before mainshocks is present for all scale ruptures. Furthermore, real-time tracking of the seismic regularity coefficient combined with current earthquake forecasting methods may increase the probability gain of forecasting.

The study was co-financed by project 2024/WK/05 of the Ministry of Science and Education, Poland.

## AS25-0353

# Geospace weather and earthquake preparation processes. A case study on 2015 M7.8 Nepal and 2025 M7.1 China and Nepal earthquakes

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Our analysis of NOAA data from March to April 2015 detected several unusual thermal radiation anomalies (TRA) in the Himalayan region (Ouzounov et al., 2021), which remained concentrated around the future epicenters of the 2015 earthquakes three months in advance. To explain this phenomenon, we begin by studying the geospace weather surrounding the 2015 M7.8 and the more recent 2025 M7.1 earthquakes in China and Nepal. For the 2015 M7.8 event, we observed (Ouzounov and Khachikyan, 2024) that it was preceded by approximately 39 days by the St. Patrick's Day geomagnetic storm, which began on March 17, 2015. This storm met the criteria for strong earthquake occurrence: at the onset of the magnetic storm, the high-latitude portion of the longitude where future earthquakes would occur had to lie under the polar cusp, allowing solar wind energy to penetrate the atmosphere freely. The M7.1 earthquake in 2025 was preceded by two magnetic storms that satisfied this criterion, on October 6, 2024, and December 17, 2024. The delay time between the storm onsets and the occurrence of the M7.1 earthquake was approximately 93 days and 21 days, respectively. According to the LAIC concept, we observe the activation of faults, which leads to increased emanation of geo-gases that produce additional heat flux detectable by satellites. The TRAs indicated deep fluid migration to the Earth's surface. We suggest that this may be influenced by the cumulative effect of solar wind energy deposition in the lithosphere before the rock media is ready for destruction.

## AS25-0389

# Ionospheric and meteorological anomalies associated with the earthquake in Central Asia on 22 January 2024

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This strong earthquake (EQ) provides comprehensive example of the complex response of the geospheres to seismic activity. The satellite and ground-based observations reveal a chain of elements included in the LAIC concept. Anomalies started developing over the epicenter a day before and maximized close to the time of the main shock. While flying over the EQ area, the tandem of Swarm satellites observed small-scale wave-like irregularities in the plasma density with an amplitude of ~$1.5\times10^4$ el/cm$^3$ that are likely associated with co-seismic electric field penetrating the ionosphere. The local anomaly occurred against the background of global increase in electron content since the quake coincided with the ionospheric response to a solar flare (although geomagnetic indices remained quiet). We propose to analyze the difference between observations of pared satellites rather than the absolute values of plasma density. In this way, the ambiguity associated with the definition of the reference field can be avoided. The ionospheric anomaly is consistent with simultaneously observed disturbances of meteorological parameters in the EQ region. The MERRA-2 specific humidity, latent heat flux, and aerosol optical depth exhibit co-located disturbances that can be attributed to the effect of increased ionization rates of tropospheric air and its subsequent decay, that results in perturbations in electrical conductivity of the near-Earth boundary layer associated with preparation of the seismic event. This research was funded by the Ministry of Science and Higher Education of RK, grant IRN-AP19677977.

## AS25-0390

# Global distribution of VTEC anomalies in relation to tectonic plate boundaries

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Atmospheric responses to earthquakes or volcanic eruptions are described in many studies, and it is well known that their observation can potentially contribute to forecasting of natural hazards. In the studies on so-called lithosphere–atmosphere–ionosphere coupling (LAIC) the researchers investigate small-scale ionospheric perturbations related with gravity waves after strong earthquakes or larger-scale local changes of VTEC called TEC enhancements. These larger-scale anomalies are often temporally connected to geomagnetic storms, but their link with strong earthquakes has been also proven. The present study refers to the larger-scale VTEC anomalies only, and brings additional observations proving that direct linking of TEC enhancements with single individual large earthquakes doesn't solve the issue. The application of UQRG VTEC maps from the Polytechnic University of Catalonia (UPC) IonSAT group makes reliable the detection of high-resolution VTEC changes. Our study describes global relative and normalized VTEC variations, which have spatial and temporal behavior strongly indicating their relationship both with geomagnetic changes and the tectonic plate system. Additionally, the occurrence of TEC enhancements is observed more frequently over oceanic spreading ridges/transforming faults than over the subducting boundaries. These boundaries are described in the literature as representing a higher conductivity in comparison to surrounding structures, particularly at greater depths. Therefore the indicated diverging plate junctions are suspected to play a significant role in the lithosphere–ionosphere energy transfer.

## AS25-0532

# Characteristics of magnetic field disturbances in the ionosphere

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Magnetic field disturbances related to earthquakes could be taken from high-precision magnetic measurements observed by Low-Earth-Orbit (LEO) satellites. However, magnetic signature of a few nanotesla may be caused by many different factors, such as the ionospheric / magnetospheric processes and electric currents. To better identify earthquake-related disturbances, a thorough analysis and understanding of these magnetic field disturbances are still lacking.

This study aims to investigate the characteristics of magnetic field disturbances at the LEO altitude and explore their driving or influence factors. We used 50 Hz magnetic field data provided by Swarm satellites, and developed a disturbance extraction method. Our results indicate that (1) Occurrence rates of disturbances differ between middle and low latitudes and high latitudes. The large-scale field-aligned currents in the polar region should be the primary cause of the high occurrence of disturbances during the day and night at high latitudes; (2) At middle and low latitudes, occurrence rates during day and night depend on season and longitudes. Occurrence rate is low in equinoxes. The longitudinal dependence is clearer at night; (3) Global occurrence of midlatitude disturbances at night is similar to those in the previous papers, and is generally consistent with features of nighttime medium-scale traveling ionospheric disturbances. Daytime magnetic field disturbances have not been fully discussed. Effects of solar quiet (Sq) and related interhemispheric field-aligned currents may be major factors. More data include solar maximum and minimum periods are still in analysis to further understand these disturbances, and to facilitate earthquake application research.

## AS25-0631

# Recent achievements on short-term seismic hazard forecast by Robust Satellite Techniques

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Anomalous transients in the Earth's thermally emitted radiation have been often associated with the preparation for major earthquakes. The Robust Satellite Techniques (RST) approach has been proposed in order to provide a clear definition of thermal anomalies as well as to try to discriminate the ones possibly associated to earthquakes occurrence from the ones associated to others (e.g. meteorological) causes. In this study recent achievements and known limits of such an approach are discussed with reference to its applications to different satellite sensors, different geographical regions and geotectonic settings also in the perspective of a multi-parametric system for a time-Dependent Assessment of Seismic Hazard (t-DASH).

## AS25-0682

# Electromagnetic signatures linked to deformation and moderate earthquakes: case studies from Andaman-Nicobar subduction zone and Himalayan collision zone

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We investigate pre-earthquake seismo-electromagnetic (SEM) signatures of geomagnetic data across two different tectonic environments: the subduction zone of Andaman-Nicobar and collision collison zone of Himalayan region. We analysed vertical component of the geomagnetic field to extract the SEM signatures associated with moderate magnitude earthquakes (M 4.0–5.3) occurring within of 250-kilometre radius from geomagnetic recording station. Fractal and multi-fractal analysis of data from the Nicobar region of three active faults (Seulimeum Strand fault (SS), West Andaman fault (WAF), Andaman Trench (AT)) show distinct anomalous signatures: the signatures dominated in positive width multifractal spectrum ($q>0$) indicating low-frequency perturbations corresponding to earthquakes of SS fault. The enhanced monofractal dimensions and negative width multifractal spectra ($q<0$) are prominent for activities along WAF & AT fault, suggesting high frequency SEM signals. In the Himalayan region the seismic activity along the Main Central fault (MCT) are showing the SEM signatures in monofractal and negative width multifractal ($q<0$) parameters, indicate high frequency SEM signatures. These moderate magnitude earthquakes are associated with SEM signatures prior to a week to month from earthquake events. The consistence appearance of SEM signatures week to month before suggest potential for inter-mediate-term earthquake forecasting after further validation with other and larger data sets.

## AS25-0716

# Changes of the local magnetic field on the Adriatic tectonic microplate before the onset of strong earthquakes

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The Adriatic tectonic microplate, due to its location and exploration, is an ideal natural geophysical laboratory. The magnetic field measured on the microplate contains a very high level of noise compared to measurements on the neighboring Eurasian tectonic plate. This noise has been found to originate from multiple sources, including weather front passages, changes in the Moon's position, and tension in the microplate before earthquakes. Two destructive earthquakes that happened during the initial minimum of the current 25$^{th}$ solar cycle are discussed.

The initial phase of a G5 category geomagnetic storm, one of the twenty most powerful magnetic storms in the last 500 years, was registered on May 11, 2024. From the results of measurements taken at the geomagnetic observatory (Piran, Slovenia), standard geomagnetic indices K were calculated, which are determined only from the change in the horizontal component. The daily acceleration in the change in the energy density of the magnetic field was also calculated. The effectiveness of such a combined evaluation was checked on measurement data for one effective rotation of the Sun. Previously determined limit values of exceptional events served as a reference for all future as well as for all previous such events. Measurement results for the year 2000 were specially processed due to the occurrence of two very strong earthquakes in the immediate vicinity of Slovenia.

## AS25-0720

# Trend slowdown of GNSS coordinate timeseries before larger earthquakes in South California

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According to rock rheology, if the confining pressure of rock is near the brittle strength of the rock, a transition from brittle to ductile behavior will occur, which may cause slowdown of displacements as rock may firstly undergo on a stage of building up stress without creep. In this research, the filtered timeseries of horizontal displacement of continuous GNSS stations is obtained at first and a trend-diversion method is developed to find the trend slowdown of the time series. By using the open data of GNSS/GPS station position timeseries from the Nevada Geodetic Laboratory, we find the trend slowdown of displacement timeseries occurred at most GNSS stations nearby the epicenters of several historical larger earthquakes in California with magnitude greater than 6.0, most of them present the trend slowdown in two weeks or one month before the earthquakes occurred. With automatic daily detection of the trend slowdown in both space and time by using coordinate timeseries of continuous GNSS stations, this method can hopefully be applied to predict larger earthquake in active tectonic regions, such as South California and Japan islands where dense continuous GNSS stations are running.

## AS25-0736

# Temporal ionosphere electric currents triggered by 2024 M 7.4 Hualien earthquake

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On April 2, 2024, an M 7.4 earthquake struck the eastern Taiwan region, China, triggering geomagnetic disturbances. We analyzed three-component geomagnetic data with 1 Hz sampling rate of eight stations ranging ~84–320 km from the epicenter. Our findings reveal the simultaneous geomagnetic disturbances in both the X and Z components at stations within 114 km of the epicenter. These disturbances persisted for 350 to 413 seconds, with peak amplitudes of 0.45 nT and 0.3 nT in the X and Z components, respectively. The Z-component disturbances exhibited opposite phases across the affected stations, suggesting the presence of electric currents near the epicenter. The time delay between the earthquake and the geomagnetic disturbances aligns with the propagation of acoustic waves from the epicenter to the ionosphere. Utilizing the Biot-Savart law, we estimated the location and intensity of the electric currents responsible for these disturbances. Our calculations place the currents approximately 17 km north of the epicenter, at an altitude of ~75 km, with an intensity of ~120 A and an azimuth of 301.5°. In addition, observations from high-frequency Doppler sounders supported that acoustic wave propagated to the lower ionosphere, generating electric currents that led to the observed simultaneous geomagnetic disturbances, and continued upward to perturb the higher ionosphere. This study reveals a novel class of earthquake-triggered geomagnetic variations, offering new insights into the interaction between seismic events and the ionosphere.

## AS25-0897

# The 2025 Santorini-Amorgos seismic crisis: The operational response of the Institute of Geodynamics, National Observatory of Athens (NOA-IG)

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An unprecedented seismic swarm with up to 230 events of magnitude greater than M4.0, took place at a distance of only 25–45 km far from the area of Santorini and Kolumbo volcanic centers in February, 2025. The seismic sequence followed a 6-month period of unrest in the intra-caldera region of Santorini, where a bulk of microseismicity and moderate deformation rate were recorded. The sequence registered 210 events (M≥4.0) in a period of only two weeks, which is more than twice, or even triple, the annual rate of the broader area of Greece.

The operational response of NOA-IG, responsible for monitoring the 24-hour seismicity in Greece, was instant. A number of immediate actions were undertaken, including personnel increase in the monitoring center, installation of new seismological, accelerographic and GNSS stations as well as tide gauges and other geophysical instruments, to provide a more precise evaluation of the seismic parameters and the associated hazard in real-time. Beyond the real-time seismicity analysis, research groups of the institute developed local velocity models to improve location accuracies, performed statistical analysis and enriched the seismicity catalogue by applying machine learning techniques. With this instant response, NOA-IG succeeded in providing critical information regarding the evolving seismic crisis to all interested parties, including decision makers, state and scientific committees, interested stakeholders and the general public.

## AS25-0926

# Geochemical features and seismic imaging of the tectonic zone between the Tibetan Plateau and Ordos Block, central northern China

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The Tibetan Plateau is growing by both vertical uplift and horizontal extension. It is a continuing debate how the Tibetan Plateau interacts with its surrounding plates and blocks. This study investigated the spatial distribution of gas geochemical anomalies (e.g., high flux of CO2 in correspondence of the main faults) at regional scale together with the seismic tomography in correspondence of this tectonic zone with the aim to figure out the domain of convergent boundary between the Ordos block and Tibetan plateau, and trace the tectonic discontinuities which are able to transfer fluids through the crustal layers between the two main geological units. From northwest to southeast, obvious difference of spatial distributions of geochemical and geophysical features in the tectonic zone between the northeast margin of the Tibetan Plateau and the Ordos Block is inferred. The northeast area (Zone A) is dominated by thrust and strike-slip faults with clear velocity boundary underneath. The southeast area (Zone C) is dominated by extensional tectonics with roughly E-W fast-velocity direction (FVD) of P-wave azimuthal anisotropy. The intermediate area (Zone B) also dominated by thrust and strike-slip faults is an extraordinary zone, where intensely locked-fault were clearly revealed, while the predominant anisotropic FVDs in the middle crust changed obviously, more contribution of shallow gas component was detected, and CO2 flux, heat flow, and regional $\varepsilon$, $\xi$, and $\sigma$ in the upper crust were higher. The adopted multidisciplinary approach demonstrated that Zone B is the convergent boundary between the Tibetan Plateau and the Ordos Block.

## AS25-0928

# Design of the PRELUDE CubeSat for the study of ionospheric D-region earthquake precursors

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Despite advances in satellite remote sensing, forecasting large earthquakes remains a major challenge due to the unpredictable nature of these events. To address this challenge, our study, building on the achievements of the French DEMETER satellite, focuses on atmospheric and space electrical variations as potential indicators of ionospheric D-region precursors to earthquakes. This approach is expected to contribute to the improvement of short-term forecasting abilities. To this purpose, we would like to introduce our CubeSat PRELUDE (Precursory electric field observation CubeSat Demonstrator), a nano-satellite dedicated to earthquake precursor detection and physical mechanism elucidation. PRELUDE is scheduled for launch in JFY2025 as part of JAXA's Innovative Satellite Technology Demonstration Programme. This study presents the results of the system design, development and mission planning of PRELUDE, which aims to elucidate the physical mechanisms behind the statistically significant ionospheric phenomena of earthquake precursors. PRELUDE is an 8 kg, 6U CubeSat specialized in VLF electromagnetic wave intensity observations. To achieve miniaturization, it incorporates a drive recording function to downlink only the data around the EQ epicenter to ground stations, reducing data storage and transmission requirements. It also hybridises the Langmuir and electric field probes typically found on satellites weighing over 100 kg, such as DEMETER, into a compact design suitable for CubeSats weighing just a few kilograms. The hybrid sensor unit extends the outriggers bidirectionally by 1.5 m from the satellite using a folding extension mechanism. In this presentation, we show the satellite design requirements for elucidating the mechanism of earthquake precursor phenomena.

## AS25-0970

# Fracture-Induced Electromagnetic Radiation (FEMR) Technique as a Precursor to Earthquakes: Observations from the Dead Sea Transform (DST) Fault System

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Comprehending pre-earthquake processes through interdisciplinary approaches is crucial for advancing seismic hazard assessment. The Fracture-Induced Electromagnetic Radiation (FEMR) technique is a novel geophysical tool that assesses recent crustal stresses, identifies active faults, and can detect stress variations in brittle rocks concerning tunnels and mining excavations. Its attribute of an anomalous increase in amplitude and activity prior to a macro failure makes it a prolific precursor to earthquakes. The FEMR technique operates by detecting naturally occurring electromagnetic signals emanating from the deformation of fractured rocks. This study has conducted FEMR surveys along the seismically active region of the Dead Sea Transform (DST) fault system at nine locations from the Sodom region in the south to the Jericho region in the north. Incidentally, this coincided with the Mw 6.3 aftershock that followed the devastating Turkey-Syria earthquakes of February, 2023. FEMR parameters such as pulse frequency, hit rate, accumulated energy, and Benioff strain release were analyzed for temporal variations leading up to the aftershock. The results indicate a systematic increase in FEMR activity in the hours preceding the seismic event, demonstrating a clear correlation between stress accumulation and electromagnetic emissions. The study highlights the role of FEMR in detecting stress changes in the lithosphere and its correlation with geophysical precursors associated with seismic activity. This work underscores FEMR's applicability as a real-time monitoring technique for earthquake precursors. The findings contribute to the growing field of interdisciplinary seismic precursor studies and provide a step forward in understanding the dynamic processes leading to earthquake nucleation.

## AS25-1002

# Interdisciplinary monitoring of seismic precursor factors

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NIEP, a research and development institute in Romania specializing in earth physics, has developed a multidisciplinary sensor network whose main task is earthquake prediction and which has now been adapted to study the effects of climate change. The phenomena that occur before an earthquake require interdisciplinary research, data over long periods of time for offline analysis and real-time information. The NIEP network includes a seismic network, devices for measuring gas emissions (radon, CO2, CH4), infrasound, acoustic waves in the air, magnetic and telluric fields, solar radiation, and meteorological data. The monitoring network ensures real-time data acquisition as well as servers for storing and analyzing the information from the monitored areas. Seismic data is monitored in the form of analyzes of the parameters a – b of the Gutenberg-Richter relation. An example of an analysis of the coupling of the lithosphere- atmosphere- ionosphere is carried out at the multidisciplinary monitoring station in Vrancioaia, where we have equipment for measuring infrasound in the air and on the ground (EMFIT), radon, ground surface temperature, solar radiation, electrostatic field of the atmosphere, ionization, meteorological equipment, seismometers and accelerometers. At this site, the noise generated by cracks and/or rock splitting due to ground deformation before and after an earthquake is monitored acoustically with a sampling frequency of 20 kHz. The results are presented in real time on the website http://afros.infp.ro/AFROS_en.php?link=dategeofizice.

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## AS25-1003

# Comprehensive Spatio-Temporal Statistical Investigations of Seismicity in Correlation with Geophysical Field Variations

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The spatio-temporal distribution of seismicity requires a priority re-evaluation based on the latest data and improved catalogs. Statistical seismicity analysis techniques include time-dependent fractal dimension analysis, the calculation of Z and PI/RI parameters, the b-value, as well as seismic energy assessment and their variations in time and space. A key contribution of this study is the development of testable algorithms tailored to Romania's seismicity, and their application for the last 15 years for intermediate depth earthquakes from Vrancea. These analyses contribute to seismic hazard assessment while also laying a solid foundation for short-term earthquake forecasting in correlation with geophysical field observations. This study explores the correlation between multidisciplinary precursor observations, including the Earth's magnetic field, temperature and humidity, atmospheric electrostatic field, and subionospheric propagation of low- and very-low-frequency radio waves. It is a novel aspect is the correlation between seismic energy release and anomalous geomagnetic field variations, providing new insights into geomagnetic precursors.

Our approach is twofold: (1) correlating geomagnetic field variations with seismic activity through seismic parameters variations and (2) analyzing their relationship with other possible precursory parameters. To better quantify the link between recorded anomaly magnitudes and released seismic energy, standard deviation filtering was applied to isolate variations due to solar activity, thereby highlighting potential seismic precursors.

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## AS25-1029

# Ionospheric Currents Driven by Teleseismic Rayleigh Waves from the 2011 Tohoku Earthquake

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Seismo-magnetic disturbances (SMDs) are transient magnetic field anomalies, induced by seismic waves coupled via atmospheric acoustic gravity waves (AGW) to the ionosphere. Using data from 52 geomagnetic stations and 764 seismic stations, we provide a detailed view of electric currents associated with a travelling SMD triggered by the 2011 Tohoku earthquake (Mw 9.0). We apply a novel array data processing scheme to effectively remove background geomagnetic variations, allowing clear identification of magnetic perturbations travelling across the array. The SMDs lag Rayleigh wave phase arrivals by 6–8 minutes, corresponding to the time required for acoustic waves to propagate to ionospheric altitudes (110–160 km). The SMDs appear as pulsations at lower frequency than the driving seismic pulse (4.8 vs. 5.6 mHz), and have much higher Q, with ringing at some sites persisting for 20 minutes or more. Both the frequency shift, and the ringing, are consistent with known AWG resonances, which contributes significantly to effectiveness of the ground-ionosphere coupling. Equivalent ionospheric currents inferred from our array are organized as concentric oscillating circles, centered on the epicenter. These current loops propagate outward with the Rayleigh wave phase velocity (4.08 km/s), but with substantial ringing after passage of the seismic peak.

## AS25-1049

# Foundations for an operational earthquake prediction system and possible developments

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Earthquake prediction is one of the most challenging enterprises of science. According to the issue for the 125th anniversary of Science journal, appeared in 2005, an important question is whether earthquake precursors are existing and could be useful for earthquake prediction. We present methods to detect potential pre-earthquake anomalies, that can be considered reliable earthquake precursors, on the base of which we can make a robust operational earthquake prediction system. In particular, we show the analysis of lithospheric, atmospheric, and ionospheric data and the detection of anomalies under specific criteria. When we apply these methods retrospectively, we find that their accuracy goes from 0.69 to 0.83. The combination of two or more methods is expected to improve the accuracy and decrease the false alarm rate.

## AS25-1117

# Earthquake coupling processes into the ionosphere derived from electric and magnetic field measurements

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We investigate electric and magnetic field variations related to magnitude M ≥ 5 earthquake events in European areas of high seismic hazards. The aim is to capture a comprehensive picture of intricate interactions taking place before and during the earthquake events. Sub-ionospheric waveguide measurements (upper boundary D/E-layer ionosphere, altitude ~ 60–90 km) from the ground-based INFREP VLF/LF receiver network are used to study electric fields from narrowband transmitter-receiver radio paths close to earthquake epicentres. By complementary magnetic field observations from ESA's Swarm mission (F-layer ionosphere), and exploring the efficacy of space-based techniques, one can possibly supplement the characterisation of the propagation channel from the lithosphere up to the low earth orbit at ~ 500 km altitude. The signals are analysed in the time and frequency domains and statistically evaluated. Environmental influences, like geomagnetic disturbances and complex atmospheric patterns, are considered. Spatial and temporal proximity to the event sites is necessary to achieve an adequate signal-to-noise ratio in the field measurements.

Our findings indicate a threshold magnitude of M ~ 5.5 to characterise earthquake processes in VLF/LF electric field variations based on the so-called night-time amplitude method. While a detailed coupling mechanism hasn't been confirmed yet, a physical explanation for the observed pre- and co-seismic variations is based on atmospheric gravity waves (AGWs) excitations. We emphasise the importance and synergetic effect of long-term multi parameter investigations together with the necessity of international scientific cooperations to develop a more comprehensive understanding of earthquake processes and mitigate societal impacts.

## AS25-1156

# Crustal Deformation Research Using Pseudo-Strain Gauges with GNSS Data

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An investigation of the relationship between changes in the correlation coefficients of the orthogonal components of four-component borehole strainmeter data and earthquakes in China reported that the correlation coefficients, which are normally close to 1, decreased to 0.2 just before several significant earthquakes. In addition, a study of the relationship between network connectivity and earthquakes using correlation coefficients between stations of multiple borehole strainmeter data reported that anomalies tended to increase 20 days prior to earthquakes. In Japan, 67 strain gauges have been installed, but there is a limit to the number and regional bias. Therefore, using the GNSS continuous observation system (GEONET ) deployed by the Geospatial Information Authority of Japan (GSI) at approximately 1,300 locations throughout Japan, we decided to construct a pseudo-strain gauge consisting of four GEONET observation points to index the amount of crustal deformation. Then, we investigated the relationship between the network connectivity calculated from the correlation coefficients among the pseudo-strainmeter stations and earthquakes. In this report, we report the results of our attempts to extract variations before and after the 2016 Kumamoto earthquake (Mw 7.0), the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0), and the 2024 Noto Peninsula earthquake (Mw 7.5). These analyses help to consider seismo-electromagnetic phenomena and LAIC mechanisms.

## AS25-1176

# Scaling properties and anomalous diffusion of the Santorini-Anydros-Amorgos, 2025 swarm seismic activity

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Swarm earthquake activity associated with pore-fluid pressure diffusion in the crust can frequently be observed, particularly related with fluid diffusion. Increased seismicity has been observed during January to March 2025 in the area between Santorini and Amorgos in the vicinity of Anydros isle (South Aegean, Greece) near the submarine Kolumbo volcano. Using the earthquake catalog for the area, we use concepts of non extensive statistical physics to study the spatiotemporal and diffusion properties of swarm seismicity and investigate the possible involvement of fluids in the triggering mechanism. The activation is divided in three periods. The first and third periods are slow subdiffusion process. During the second period of activation, events are migrating towards indicating a super-diffusive process. The estimation of the mean square displacement of seismicity with time during the first and third main periods of activation shows very weak earthquake diffusion while a more pronounce earthquake diffusion during the second period observed, with a diffusion exponent that corresponds to a super-diffusive process. In addition, we use non-extensive statistical mechanics to study the spatiotemporal scaling properties of seismicity, with results that indicate correlated behavior and organization patterns during all periods of activation. Observations and analysis indicate the possible involvement of fluids in the triggering mechanism of the Santorini-Anydros-Amorgos, 2025 earthquake swarm.

## AS25-1205

# Variations in the East-North-Up Coordinate System Observed During the 2023 Kahramanmaraş Earthquakes in Türkiye

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The 2023 Kahramanmaraş earthquakes in Türkiye provided a significant opportunity to examine the performance and variability of the East-North-Up (ENU) coordinate system in high-magnitude seismic events. This study investigates how local ENU frame definitions, instrumental orientations, and geodetic reference systems influenced the analysis and interpretation of seismic and geophysical data collected during and after the earthquakes. Variations in ENU implementations are observed across regional GPS stations, seismic networks, and InSAR-derived deformation models. Differences in local geoid models, transformation methods from global Earth-Centered Earth-Fixed (ECEF) coordinates, and station-specific orientation protocols introduced inconsistencies in the alignment of displacement vectors and seismic wave propagation analyses. We analyze the impact of these variations on fault slip estimation, co-seismic displacement calculations, and post-seismic deformation monitoring. Our results demonstrate that even minor inconsistencies in ENU definitions can propagate into significant discrepancies in multi-source data integration, affecting both real-time hazard assessment and long-term geodynamic interpretations. To address these challenges, we propose standardization strategies for ENU frame establishment in seismically active regions, emphasizing the importance of consistent metadata documentation and regional coordination. This case study contributes to the ongoing development of best practices for coordinate system management in the context of complex, high-impact seismic events.

## AS25-1279

# Comprehensive precursory processes analysis of multiple earthquake case studies from a multiparametric and multilayer point of view

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The study of the preparatory phase of large earthquakes is a crucial and challenging topic. Due to the severe impact of their effects on society in terms of fatalities and damage, it is fundamental to understand the physical phenomena involved in this process. In order to characterise those physical phenomena, the first step is to collect as many data sources as possible that can provide information about this natural hazard, and that are potentially expected to present anomalies within the lithosphere-atmosphere-ionosphere coupling (LAIC) model. In recent years, through the Geosystemics concept, our group has analysed several earthquakes by collecting data from different geolayers — i.e. the lithosphere, atmosphere and ionosphere — to establish a possible chain of processes linked to the preparatory phase of large and shallow earthquakes (typically with a magnitude greater than 5.5 and a depth of less than 50 km). This is because these earthquakes are more likely to generate signals that can be detected at satellite heights. We propose here a comprehensive analysis of all the case studies we have examined with similar methodologies, to shed light on the different anomalies that can be detected before various earthquakes occur (striking in different tectonic contexts), the similarities and differences between them and the lessons we have learned about the lithosphere-atmosphere-ionosphere coupling.

## AS25-1339

# "Hidden" Physical (Space) Parameters Influencing the Electromagnetic Environment of Earth Before Large and Giant Earthquakes

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In a previous study (Anagnostopoulos et al. 2021) we have demonstrated that both the giant earthquakes and the highest global seismic energy release, during a period as long as 118 years (1900–2017), occurred during periods of space conditions with low sunspot numbers (LSNs), and in particular during the ascending and the descending phase of solar cycles. In the present case study we examine the space weather before some well known giant or/and catastrophic earthquakes such as Taiwan Chi-Chi (1999), Sumatra (2004), Chile (2010), Japan (2011) and Kuyamoto (2016). In our study we found that all of these earthquakes did occur during times of LSNs and were preceded by space conditions with solar wind sub-ULF (Alfvén) waves impeded in high speed solar wind streams (and some more solar wind variations). These space waves were found to be related with certain changes in the electromagnetic environment all the way from the ionosphere to the Earth's surface. The comparison of simultaneous space, ionospheric, atmospheric and terrestrial observations in the cases we examined demonstrate that hidden (space) space physical parameters control a long array of earthquake electromagnetic signals. Moreover, our analysis supports the concept put forward by Anagnostopoulos (2021) that sub-ULF Alfvén waves impeded in high speed solar wind streams under conditions with LSNs, provides significant contribution in earthquake preparation processes.

## AS25-1342

# Identification of electromagnetic anomalies associated with seismic activity through 1D magnetotelluric monitoring in Colombia (South America)

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In this study, we correlated apparent resistivity variations with seismic activity by applying 1D magnetotellurics (MT method) using a multiparametric station (TUNJ) of the Geophysical Network of the National University of Colombia (RGUNAL). This station is located in Tunja, Boyacá, in the Easter Andean Cordillera, central Colombia. We developed a specific seismic data base according to the following parameters: magnitude > Mw.4.0, depth of the earthquake < 60 km, and distance to the epicenter < 100 km, from 2018 until 2023. Some positive results were found in a seismic event on April 26$^{th}$ 2020 UTC: 03:29:33, located in Sabanalarga, Casanare. (Lon =-73, Lat =4.889, depth = 51.88 km). Anomalies were observed 8 h before the main shock, and the anomalies were found at the same depth as the earthquake's hypocenter. A possible explanation for this phenomenon could be related to fluid migration due to the stress regime before, during, and after the earthquake. The results show that fluid migration before a seismic event might generate pore pressure gradients, thereby changing the electromagnetic field.

## AS25-1459

# Correction for geomagnetic secular variation effects: a new method for identifying tectonomagnetic anomalies

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The study focuses on calculation of geomagnetic secular variation and the respective correction of tectonomagnetic data. A new technique is proposed for picking the secular variation component in the Earth's main magnetic field recorded by precise measurements at 100 to 500 km sites on the surface. Long-period field variations presumably arise from fluid motions in the liquid core, at depths of 3000 km, whereas the sizes of observation networks are within 500 km. The sources of secular variation, irrespective of their configuration, are much deeper than those of tectonomagnetic anomalies located above the Curie surface depths of ~15 to 30 km. Therefore, the surfaces that represent the space distribution of secular variation must be smoother than the respective surfaces for tectonomagnetic anomalies. The problem is thus to separate the regional and local signals from the two types of sources located at different depths. The method is tested using data of yearly geomagnetic measurements at more than 30 repeat stations of a ~120 km long geodynamic network in Gorny Altai (2003–2023) and more than 100 stations of a ~400 km long network near Baikal Lake spanning the period from 1997–2024. The secular variation pattern is reconstructed by quadratic polynomial interpolation, which is sufficient for the required accuracy of calculations of geomagnetic secular variation. The precise data corrected for secular variation of the main field revealed previously hidden tectonomagnetic anomalies up to several nT intensity that could be associated with earthquake preparation processes at these regions.

## J06 Combined GNSS, Ground, and Satellite Data to Study Co-Seismic Parameters Associated with Natural Hazards

### AS25-0150

# Ionospheric anomalies few hours before the magnitude 7.5 Northern Peru earthquake: GNSS and swarm satellite observations

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We investigated pre-seismic ionospheric disturbances (PIDs) associated with the Mw 7.5 Northern Peru earthquake on November 28, 2021, using GNSS and SWARM satellite data. Significant anomalies in Total Electron Content (TEC), electron density, and electron temperature were observed up to two hours before the mainshock. Disturbances were recorded at different times by GNSS receivers and the SWARM satellite. For example, the "cruz" receiver detected a TEC amplitude of 0.22 TECU at 9:00 UT, which increased to 0.56 TECU by 10:30 UT, while "riob" recorded a TEC amplitude of 0.11 TECU at 9:00 UT, rising to 0.62 TECU by 10:30 UT. Spectral analysis using the Short-Time Fourier Transform revealed center frequencies ranging from 3.46 mHz to 5.94 mHz, within the acoustic/infrasonic range, indicating the possible influence of acoustic-gravity waves, potentially triggered by foreshocks. The disturbance amplitudes increased as the earthquake approached, suggesting dynamic coupling between the lithosphere-atmosphere-ionosphere (LAI) system. These ionospheric variations likely reflect crustal stress changes, influenced by acoustic waves, electromagnetic coupling, and seismic energy. Our findings provide new insights into the ionospheric response to large earthquakes and highlight the potential for ionospheric monitoring as a complementary tool for early seismic warning systems.

## AS25-0378

# Enhancement of Water Vapor and Changes in Meteorological Parameters Associated with Cyclones in the Bay of Bengal and Arabian Sea

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The Bay of Bengal, Arabian Sea and Indian Ocean surround the southern part of India. Every year, cyclones are formed in the Bay of Bengal and in the Arabian Sea, these cyclones move towards coast and landfall occur. Sometime these cyclones move along the coast in the north, the impacts of cyclones are observed over the Indian land region. The impact of cyclones is seen due to heavy precipitation, sometimes the coastal areas get flooded. With landfall, the impacts are observed in the agricultural fields, uprooting of the trees and damage to the buildings, roads and existing infrastructures. The air quality gets affected due to aerosol mixing and transport of anthropogenic air mass from the surroundings. We have carried out detailed analysis of GPS data from the IISc Bangalore campus and used MODIS water vapor data. Water vapor shows characteristic behavior and shows a strong correlation with the precipitation especially when the cyclone is near to the vicinity of GPS station. The detailed analysis of GPS and MODIS data and relation with the observed rainfall will be discussed in the onset of monsoon. The observed water vapor, rainfall and air temperature will be discussed in the forecast of precipitation in the location, the location where likely to landfall occur to forecast the likely flooding to mitigate the impacts in flooding to save lives of people. The role of GNSS network in India will be discussed.

## AS25-0451

# Surface Deformation, Fault Model and Coulomb Stress Modelling of the 21 June 2022 Afghanistan (SW of Khost) Earthquake

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A shallow earthquake of magnitude of nearly 6.0 occurred towards the Northwest of the western indian plate boundary near the Khost region of Afghanistan. Almost 5000 lives were directly impacted where more than 1000 were reported dead and another 2000+ were injured. It also caused damage to houses either complete or partial. The Preliminary reports suggest that the earthquake event was predominantly strike-slip faulting, either left-lateral slip on a northeast-striking fault or right-lateral slip on a northwest-striking fault (USGS) occurred at a depth of 4 Km located at 33.020ºN, 69.464ºE. Although this information is consistent with the larger tectonics of the western boundary of the India plate that corresponds with the Chaman Transform, the details of actual surface deformation are lacking. The present scenario allows taking advantage of the remote sensing measurements, particularly Differential Interferometric Synthetic Aperture Radar (DInSAR) technique to pin-down the extent and nature of surface deformation. The DInSAR deformation results are inverted and a distributed slip fault model is derived that justify the co-seismic surface deformation, geology of the area and larger tectonic context of the earthquake. The fault parameters are used to study the coulomb static stress changes caused by the earthquake. The importance of our study lies in, besides the humanitarian and economic concerns, its scientific value to understand the active tectonics, source mechanism and earthquake hazard of the western transform boundary.

## AS25-0468

# Detection of seismo-ionospheric precursors for moderate shallow earthquakes in Greece using a statistical study

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In this study, we use the running median of the critical frequency of the F2 layer and the associated interquartile range to detect seismo-ionospheric precursors during the 10 days preceding the main shock. The methodology defines a confidence interval where foF2 varies. Any deviation of foF2 from this interval is considered an anomaly. Since the ionosphere is directly influenced by solar and geomagnetic activity, we also analyzed the Kp, Dst and Ap indices. This eliminates any ambiguity regarding the nature of the detected disturbances.

We successfully detected disturbances within the 10 days preceding the studied earthquakes. Given that the earthquakes dates are comparable (08/03/2008–08/07/2013) and (09/22/2012–09/16/2013), we investigated whether there is a link between the seasonal variability of foF2 and the detected anomalies. We found that ionospheric anomalies occur on equivalent dates with a concordance of more than 60% and 80%, respectively, for each pair of earthquakes analyzed. However, the correspondence in the time of appearance of these anomalies is very rare.

These results do not allow us to draw definitive conclusions about the seasonal variability of foF2 during the two study periods, which strengthens the hypothesis that the detected anomalies are seismo-ionospheric precursors. Clearly, it is interesting to consider several cases of earthquakes occurring at equivalent epochs to study the temporal variability of ionospheric anomalies during the earthquake preparation process. These preliminary results remain encouraging and open new prospects for studying ionospheric variability linked to seismic activity by simultaneously considering several parameters.

## AS25-0540

# Investigation of Ionospheric Total Electron Content anomalies as Potential Precursors to the Mw 5.8 Lone Pine, California Earthquake

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Potential ionospheric precursor associated with the Mw 5.8 Lone Pine, California earthquake, which occurred on June 24, 2020 was studied. Fluctuations in ionospheric total electron content (TEC) derived from Global Positioning System (GPS) data collected from 15 Continuously Operating Reference Stations (CORS) across California was considered. A statistical assessment of TEC variations was conducted within a 30-day window preceding the earthquake to identify abnormal fluctuations potentially linked to seismic activity. Solar activity (F10.7) and geomagnetic storm (Ap index) conditions were analyzed to assess their influence on TEC fluctuations and to distinguish seismic-induced anomalies from space weather effects. To ensure the robustness of anomaly detection, two stations closest to the earthquake epicenter, p465 and p467, situated at distances of 14 km and 17 km, respectively, were used as reference points. A significant negative deviation in TEC values was identified between June 12 and June 22, 2020, indicating an anomalous period prior to the seismic event. TEC data revealed a distinct low-TEC density zone concentrated in the ionosphere directly above the earthquake epicentre. This anomalous TEC distribution suggests positive correlation between ionospheric disturbances and underlying tectonic stress accumulation in the Earth's crust. The observed anomalies align with the Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) hypothesis, which posits that stress-induced changes in the lithosphere can propagate into the atmosphere and ionosphere as variations in TEC. This observation supports the potential of ionospheric TEC variations as earthquake precursors. Therefore, TEC ac as a potential tool for seismic hazard assessment and early warning systems.

## AS25-0580

# Geodetic model of the 22 January 2024 Mw 7.0 Wushi earthquake and Mw 5.7 aftershock from InSAR data inversion

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On 22 January 2024, a Mw 7.0 earthquake struck Wushi County, northwestern China, within the southern Tian Shan Mountains, causing damage and casualties. Using InSAR data (Sentinel-1), we constrained the fault geometry and coseismic slip distribution of the mainshock, as well as the source of the Mw 5.7 aftershock.

Our results indicate rupture along a transpressive, left-lateral, NNW-dipping high-angle fault, likely the Maidan fault, with slip up to 3.5 m between 10–20 km depth. The hypocenter position suggests bilateral ENE-WSW rupture directivity. Modeling of postseismic deformation, including the 29 January Mw 5.7 aftershock, suggests slip of up to 90 cm on a shallow back-thrust segment, matching observed surface breaks.

We propose a structural and/or lithological control on rupture extent, consistent with other intracontinental earthquakes. Coulomb stress analysis indicates the Mw 5.7 aftershock was triggered by the mainshock and that stress increased at both fault terminations, particularly along the Maidan fault's southwestward extension. Additionally, a wide up-dip patch remained unruptured, potentially accommodating aseismic deformation or future ruptures. This poses an ongoing seismic hazard to Wushi County and surrounding areas.

## AS25-0699

# Regional Ground Deformation Using GNSS Data and Observed Seismicity in the Northern India

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In the Delhi-National Capital Region (NCR), located in the stable plate interior of northern India, numerous faults are located that are responsible for moderate seismicity. The observed seismicity is found to be associated with extreme precipitation and groundwater withdrawal. The long-term analysis of GNSS, precipitation, and groundwater storage data from GRACE satellite and InSAR time series and water level data study the relationship between deformation patterns and co-seismic activities. The GRACE storage data show a continuous declining trend in groundwater storage at a rate of 2.5–3 cm/yr, influenced by precipitation uncertainty (60–80 cm/yr) and groundwater level. Continuous hydrological stress (climate impact and anthropogenic pumping) leads to aquifer compaction, causing segregated patches of deformation (~1.1–14.39 cm/yr), evident by topographical lows (land subsidence) and highs (upliftment) in urban centres in Delhi and surrounding areas. These deformation areas are correlated with groundwater levels (60–80 m). GNSS observations (2019–2021) in Delhi and surrounding areas show subtle uplift at a rate of 0.4 ± 0.22 cm/yr, showing the role of observed deformation patterns with the observed seismicity. The coexistence of reverse and normal faults in stress transition zones may lead to localized subsidence and uplift, suggesting that both tectonic and pore-elastic processes play an essential role in the observed seismicity. These patterns align with the structural framework of Delhi and surrounding regions to attract the attention of the Government to manage groundwater resources in view of groundwater depletion and extreme precipitation to avoid adverse impacts of seismicity and subsidence affecting the buildings and infrastructures in Delhi and surrounding regions.

## AS25-0754

# Automatic detection and localization of co-seismic ionospheric disturbances (CSID)

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Submarine Earthquakes can generate large tsunami waves with potential disastrous impacts on coastal populations. It is therefore critical to assess the tsunamigenic potential of an event by determining its magnitude, location, and surface displacements. To refine the current early warning system based exclusively on seismic data, it has been suggested to consider the earthquake-induced ionospheric perturbations in the ionospheric plasma density known as CoSeismic Ionospheric Disturbances (CSID). These fluctuations contain critical information about the source processes and complement the limited coverage of ground stations allowing the development of accurate detection and localization techniques in Near-real-time (NRT).

In this work, we present a new framework for both the automatic detection and the localization of earthquakes from ionospheric Total Electron Content (TEC) observations in the ionosphere. We first determine the detection probability of a CSID arrival using a deep learning model and then perform the inversion using a migration-stacking procedure. We employ a Bayesian approach to account for uncertainties in detection altitude, acoustic velocity models, and prior knowledge on seismic source location and origin time. Resulting posterior distributions of source parameters can then be obtained within a few minutes making it near-real-time applicable.

## AS25-0846

# Ionospheric signatures of tsunamis: detection challenges and key parameters

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Tsunamis are one of the most destructive natural hazards causing heavy human losses. They can be generated by submarine earthquakes and/or volcanic eruptions and landslides) and it is almost impossible to forecast their impact.

A near-real-time monitoring of tsunamis is required for population's safety. Differents methods are currently used to monitor tsunamis propagation in both near field (<500 km from the source) and far-field (>500 km away the source) like seafloor pressure sensors, DART and tide gauges. However, most of tsunamigenic areas are still not instrumented and the monitoring remains very challenging. An alternative approach would be to use the ionosphere, the upper layer of the atmosphere, in order to detect tsunamis and monitor their propagation. Tsunamis propagation generate internal gravity waves that can be detected in the ionosphere within 20–60 minutes after they are generated at the ocean surface. By using measurements of total electron content (TEC) from GNSS-receivers, one can detect co-tsunamic ionospheric disturbances (TTIDs), and to estimate tsunami parameters based on analysis of TTIDs' characteristics.

However, numerous disturbances can travel in the ionosphere and can mask the TTIDs. Therefore, monitoring of tsunamis propagation requires a method detecting ionospheric perturbations, separating the ones induced by tsunamis from the others, and determining spatio-temporal features of TTIDs. The first step in this development is to create a collaborative database containing the information on TTIDs registered by GNSS receivers. This contribution will present our newly developed strategy for the detection of tsunamis from the ionosphere, and the challenges to overcome.

## AS25-0929

# Various geomagnetic variations caused by acoustic waves excited by the 2011 Mw9.0 off the Pacific coast of Tohoku earthquake

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Geomagnetic pulsations with periods of 150–160, 170–180 and 200–230 s were observed on the ground in Japan about 6 min after the occurrence of the Mw9.0 mainshock off the Pacific coast of the Tohoku earthquake on 11 March 2011. In addition, a variation with a period of ~180 s was detected simultaneously at the magnetic conjugate point of Japan (i.e. Australia), indicating that field-aligned currents were excited along the magnetic field lines. These currents could have been excited by an E-region dynamo current caused by acoustic waves from the initial tsunami source. This finding confirmed that a large earthquake can generate seismo-field-aligned currents. In addition, the distant periodic (~180 s) geomagnetic variations at the ground about 600 km from the epicentre are inferred to be excited by Rayleigh waves. Rayleigh waves propagating at the surface at a speed of 3.5 km/s excited the atmosphere. The excited acoustic waves propagated into the ionosphere and also generated the E region dynamo. At most of the observed stations showing the coherent oscillation of north-south and east-west horizontal geomagnetic variations, the direction of the coherent oscillation pointed to the epicentre. Therefore, we speculated that arc currents were flowing to generate the geomagnetic field whose coherent oscillation pointed to the epicentre, which is called seismo-arc current. Note that the geomagnetic time series data were processed by removing the global geomagnetic variation component with a transfer function and extracting the acoustic wave component with high-pass filtering.

## AS25-0940

# Surface displacement in Madagascar using InSAR technique

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Madagascar was once part of the ancient supercontinent Gondwana. Over millions of years, tectonic movements caused its separation from Africa and India, leading to its current configuration. This separation has played a significant role in shaping the complex tectonic and geological structure observed in Madagascar today, positioning it within the intricate context of the East African rift system.

To analyze the current surface deformations in Madagascar, we employed time series analysis using InSAR techniques. This involved analyzing SAR data from the Sentinel-1 satellite in descending orbit, covering the period from June 15, 2014, to December 31, 2023. We created a comprehensive database to enhance our understanding of these deformations. To validate our results, we correlated them with land cover and topographic data while checking for and correcting potential sources of noise.

Our analysis of the current surface deformation rates is crucial for isolating and understanding crustal deformations linked to earthquakes, subsidence associated with water resources, and other surface processes. Our findings indicate that surface deformation in Madagascar is influenced not only by tectonic factors but also by sedimentary dynamics, including erosion and sediment deposition. For instance, we identified fault lineaments in the Alaotra region. These faults are consistent with previous field observations, suggesting ongoing crustal deformation. Additionally, concerning sedimentary dynamics, we noted an uplift in the Tsiribihina mangrove area, potential coastal erosion in Fort Dauphin, and suspected erosion near Alaotra Lake. These observations are essential for geohazard assessments, which are utilized to develop risk prevention and mitigation strategies for policymakers.

## AS25-1277

# Strain Rate and Velocity Field in the northern part of The East African Rift System (EARS) From InSAR and GPS

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Continental monitoring of ground deformation is important for early detection, understanding deformation mechanisms, and predicting the evolution of the surface deformation. The Sentinel-1 satellite constellation provides global, free, frequent, and abundant SAR data, enabling worldwide deformation monitoring through InSAR time series analysis.

In this study, we used synthetic aperture radar (SAR) data acquired between 2014 and 2024 by Sentinel-1 satellites to investigate present-day strain accumulation along the East African Rift System (EARS) covering Eritrea, Djibouti, Ethiopia, Kenya and Tanzania and we produced a high-resolution field map over the ~800,000 km² along the EARS region using open-source time series analysis software LICSBAS (NSBAS). We have integrated available GPS data, to perform a 3D decomposition to estimate horizontal and vertical velocities. Finally, we draw a map of strain rate field of the study area.

## AS25-1298

# Integrated Remote Sensing and Geophysical Analysis of Landslide Dynamics: A Case Study of the Azazga Landslide (Algeria)

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Over the past decade, the town of Azazga (northern Algeria) has experienced recurrent slope instabilities, threatening local infrastructure and communities. Notable events include the destabilization of slopes along the Tizi Ouzou-Béjaïa corridor, characterized by steep topography, flysch and Numidian formations, and intense seasonal rainfall. These instabilities are primarily triggered by prolonged rainfall, which accelerates soil saturation, leading to natural landslides in unstable scree slopes.

This study employs Multi-Temporal InSAR (MT-InSAR) techniques using Sentinel-1 SAR data (2015–2024) to monitor ground deformation and delineate active landslide zones. Rainfall data (cumulative and delayed) were integrated to analyze correlations with slope movements. Results reveal cumulative displacement rates of up to 7 cm/year in the line of sight, with significant acceleration during intense rainfall. Active zones were validated through field studies, highlighting the role of scree in amplifying landslide risks.

Subsurface conditions were further investigated using Electrical Resistivity Tomography (ERT) and other geophysical methods. These surveys provided critical insights into soil saturation, lithological heterogeneity, and potential failure planes, corroborating InSAR-derived displacement patterns. The integration of these datasets offers a robust foundation for future development of hazard susceptibility maps, which could prioritize mitigation efforts and guide sustainable land-use planning in the region.

This multi-technique approach demonstrates the effectiveness of combining MT-InSAR, rainfall analysis, and geophysical surveys for landslide monitoring and risk assessment in Azazga. It provides a framework for early warning systems and highlights the need to avoid construction on unstable terrain, such as scree slopes, to reduce future risks.

## AS25-1317

# Source mechanism and early warning of volcanic tsunamis

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Volcanic tsunamis pose serious threats to nearby coastal communities. Our study of the 2022 Tonga volcanic event revealed that the erupted air-pressure wave was a precursor to the tsunami. Contrary to previous theories, our findings indicate that the eruption process drives both the air-pressure wave and tsunami dynamics through a coupled atmosphere-ocean source mechanism. This insight offers a new approach for incorporating air-pressure sensors into early warning systems. Related publication: **Nature's** *Communications Earth & Environment*, *https://doi.org/10.1038/s43247-024-01694-z.*

## AS25-1341

# Satellite Imagery (InSAR) for Monitoring Geological Hazards in Algeria

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Satellite-based radar interferometry (InSAR) is used for monitoring ground deformations related to geological hazards in Algeria. Several case studies are presented illustrating the effectiveness of our approach using SAR analysis. We have focused on four cases: (1) landslide triggered by the Mila earthquake of August 7th 2020 Mw4.9, and the (2) ongoing azzazga landslide (2015–2025), (3) the active fault of the Zemmouri earthquake of May 21st 2003, Mw6.8, where InSAR helps understand the tectonic deformations mechanism, and (4) the deformation induced by oil drilling accident (Houd Berkaoui OKN32, from 1992-now). All these studies enabled us to monitor the deformation over 33 years time laps using time series analysis, of ERS1, ERS2, ENVISAT and SENTINEL free SAR images achieves These studies demonstrate the potential of InSAR to improve understanding of geological hazards in Algeria.

## AS25-1453

# Investigating the impact of Seismic and Non-Seismic parameters in the evolution of Co-Seismic Ionospheric Perturbations in large earthquakes

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During an earthquake, part of a seismic energy released from the epicentre transfers to the atmosphere, generating acoustic waves, through the mechanical coupling between the earth and its atmosphere. These waves amplify as they propagate upward and reach the ionospheric heights, generating ionospheric perturbations through ion-neutral collisions. This perturbation is known as co-seismic ionospheric perturbations (CIP). The near-field CIP (~500–600 km from the epicenter) are mainly induced by the direct acoustic waves from the epicenter. Their amplitude depends on seismic factors (e.g. magnitude, depth, focal mechanism, vertical displacement) and non-seismic factors (e.g. geomagnetic field, satellite geometry, background electron density).

The present study is focused on the CIP amplitude variability induced by these factors. We select global earthquakes with magnitude (Mw) ≥ 6.5 and depth ≤110 km occurred between 2000 to 2024. Based on the Global Navigation Satellite System (GNSS) measured Total Electron Content (TEC) data, we primarily aim to quantify the CIP amplitude under the combined influence of seismic and non-seismic factors. While doing so, we are in the process of developing a numerical model to integrate seismic and non-seismic factors to estimate the CIP amplitude. We further plan to restructure the model parameters to derive the earthquake magnitude based on the measured CIP amplitudes. It is believed that the outcome of this study would be considered as an advancement in the field of ionospheric-seismology which mainly emphasis the study of earthquake parameters from the ionosphere.

## AS25-1454

# Improving Volcanic Explosivity Index (VEI) Precision: An Ionospheric based Approach

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Volcanic eruptions lead to the emission of magma, gases, and ash from the Earth' surface. The eruptions cause destruction, air pollution, and natural disasters like tsunamis occasionally if of the explosive nature. The destructive effects and threats can be minimized by monitoring and assessing the power of the eruptions. In 1982, Christopher Newhall and Stephen Self introduced the Volcanic Explosivity Index (VEI), a scale that measures the relative explosiveness of volcanic eruptions. The explosivity index is determined based on the volume of erupted material, the height of the eruption cloud, and qualitative observations. VEI is commonly expressed as an integer scale, which provides a general classification of eruption magnitude but its classification remains uncertain due to subjective estimations of eruption parameters. In the present study, we attempt to correlate the amplitude of Co-Volcanic Ionospheric Disturbance (CVID) and VEI during more than thirty volcanic events over the past two decades with an ultimate aim to better estimate the VEI from the ionosphere. We make use of Total Electron Content (TEC) perturbations measured by the Global Navigation Satellite System (GNSS) along with plume height and derive a numerical model estimating the VEI in finer scales. This new approach aims to enhance eruption classification, improve risk assessment, and deepen our understanding of the environmental impacts of volcanic activity. Furthermore, it complements existing VEI assessment methods, contributing to more accurate volcanic hazard monitoring and advancing our knowledge of lithosphere-atmosphere-ionosphere interactions during major eruptions.

## AS25-1457

# Evaluating the Potential of AI-Generated Co-Seismic Landslide Inventories for Hazard and Risk Management: Advancements and Limitations

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Co-seismic landslide inventories are essential for post-earthquake hazard assessment, susceptibility modeling, and risk-informed decision-making. Traditionally, these inventories have been produced through manual interpretation of satellite and aerial imagery—a method that, while widely adopted, is time-intensive, subjective, and constrained by limited reproducibility and data sharing. Recent advances in artificial intelligence (AI) have led to increased efforts toward automating the mapping of co-seismic landslides. Despite promising developments, current AI-based approaches remain in a developmental phase, with no existing models consistently delivering accurate, ground-truth-level inventories in the immediate aftermath of seismic events. Reported F1-scores typically range between 50% and 80%, with few studies exceeding 80%, and often only in regions overlapping with training datasets—highlighting challenges in model generalizability. To improve the reliability of AI-generated outputs, integrating auxiliary geospatial datasets, such as GNSS-derived ground displacement measurements, offers valuable support for both validation and contextual interpretation of mapped landslides. However, systematic approaches for such integration remain underdeveloped. To advance the operational applicability of AI-generated co-seismic inventories in real-time hazard response and long-term risk management, the geoscientific community must critically assess their accuracy, spatial transferability, and capacity to incorporate independent ground-based data. The development of benchmark datasets and standardized validation protocols across diverse tectonic and geomorphic settings is essential to enhance the robustness and credibility of these emerging methodologies.

## J07/S06 Historical and Legacy Geophysical data for the future: data archiving, mining and re-use of historical observations, models and numerical simulations / Pre-Instrumental Earthquake Data

### AS25-0047

# Rescue and quality control of historical geomagnetic measurement at Sheshan observatory, China

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During the International Geophysical Year (1957–1958), China set up geomagnetic observatories in Beijing, Lhasa, Lanzhou, Wuhan, Guangzhou, Changchun, and Urumqi, along with the Shanghai Observatory, forming the initial structure of China's geomagnetic observation network. These observatories have continuously observed despite challenges, accumulating valuable data and contributing to geomagnetic research. However, the scattered storage and potential damage risks threatened data integrity and reliability. This study rescued and integrated historical data from eight pioneering observatories, improving data quality and facilitating long term preservation and use. The basic conditions of the observatories, including locations, observation environments, instruments, etc., were introduced as prerequisites for data quality. The integration and processing of historical data involved collection, digitization, format unification, anomaly detection, and processing. Validations showed significantly improved data quality. These datasets are valuable for improving historical geomagnetic field models and studying variable and main fields. The data were applied to analyze Sq and geomagnetic jerks, revealing the daytime and latitudinal local time dependent patterns of Sq, and significant regional differences and asynchronous jerk occurrence times. The study aims to provide these datasets to the scientific community and public for further exploration of the geomagnetic field's spatiotemporal evolution and physical mechanisms.

## AS25-0127

# An analytical approach to investigate 3D seismogenic sources: application to historical earthquakes in central Italy

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Italy has experienced intense seismic activity for centuries. While historical seismological studies and macroseismic intensity data have improved our knowledge of past earthquakes, assessing ground-shaking of historical events (pre-1968) remains challenging due to the lack of instrumental records and uncertainties in seismogenic sources. In this study,we investigate the 3D seismogenic source geometries of historical earthquakes by integrating macroseismic, geological, structural, seismological, and geodetic data with Ground Motion Models (GMMs) and Ground Motion Intensity Conversion Equations (GMICEs). A key step of the workflow involves the residual analysis between observed and predicted intensity to identify the best-fitting sources. First,we re-evaluated macroseismic fields from the Italian Macroseismic Database (DBMI15) to refine epicentral locations and magnitudes for 201 earthquakes from the Italian Parametric Earthquake Catalogue (CPTI15) by calculating residuals between observed and predicted macroseismic intensities using an Intensity Prediction Equation (IPE), excluding observations exceeding three standard deviations in absolute value. The Boxer code re-located 26.3% of events and re-calculated magnitudes for 24%. Then,we estimated PGA and PGV at macroseismic data points using a GMM, including site amplification, and converted them into intensities using a GMICE. The average residual between observed and predicted intensities indicates the fit of the seismic source geometry. We determined the 3D seismogenic sources for 64 earthquakes in CPTI15 (1279–1984) that affected central Italy, from Mugello (Tuscany) to Sulmona (Abruzzi). Virtual 3D seismogenic boxes were constructed using fault scaling relationships, then refined with geological data and literature. This approach will be applied to identify seismogenic sources of all Italian historical earthquakes and generate reliable ground-shaking scenarios contributing to seismic hazard assessment.

## AS25-0133

# Past and future earthquakes in the Tokyo metropolitan region based on historical documents

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Tokyo (formerly Edo) has been damaged by large earthquakes. The Earthquake Research Committee of the Japanese government estimated that the future (next 30 years) probability of large (M~7) earthquakes in the Tokyo metropolitan region is 70 %. This estimate was based on the occurrence of eight earthquakes between the 1703 and 1923 Kanto (M~8) earthquakes. Among them, three events occurred in the Edo period, for which no instrumental record existed. The 1855 Ansei Edo earthquake was devastating, causing the collapse of houses and fire with estimated casualties of up to 10,000, according to historical documents. Two other events in 1782 and 1853 caused damage in Odawara city (~100 km west of Tokyo near the 1923 epicenter), but the effects on Edo were limited. Damage from five events that occurred in the early instrumental period (between 1894 and 1922) was also less significant (the largest casualties of ~ 30). Tokyo metropolitan and Japanese governments made damage estimates for future earthquakes, assuming the worst-case scenario similar to the 1855 earthquake, but its probability is not as high as 70 %.

Satake and Ishibe (2020, SRL) estimated that a total of ~2000 felt earthquakes occurred between 1668 and 1867, based on two daily records documented by the Tsugaru and Sakakibara clans. We started a systematic survey of earthquake descriptions in other official daily records as far back as 1628. Our goal is to make seismic intensity (macroseismic) data points, and to revise the future probability of damaging earthquakes in Tokyo.

## AS25-0174

# Sustainable preservation of analogue seismic data in Germany – Digitization test results

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We present the preliminary findings of our feasibility study, which seeks to evaluate the possibility of digitizing all analogue seismic data in Germany. This study is supported by the Federal Institute for Geosciences and Natural Resources (BGR) and is being carried out by a team of researchers from the University of Potsdam and the University of Hamburg.

The initial inventory of the analogue seismic data archives in Germany has been successfully finalized. Data from twelve German institutions that housed analogue seismic records has been gathered in a unified database. This database, has been released, offering extensive information regarding the archives collections.

The results from our test run, which was carried out to assess the workload associated with the ongoing scanning and digitization of seismic records, are presented. A subset of paper seismograms, together with the relevant metadata, were collected. The records underwent scanning through a range of techniques and parameters, employing various types of equipment. Subsequently, the data was vectorized.

We also examined the test event, specifically the Albstadt earthquake that occurred on November 16, 1911, to assess the techniques employed in determining earthquake source parameters, including the location of the epicentre, magnitude, and focal mechanism, using digitized analogue data. Each phase of the digitization process was be precisely documented. These guidelines were assembled into a manual, which establishes the groundwork for formulating a strategy aimed at the preservation and digitization of analogue seismic data in Germany.

## AS25-0278

# The Destructive 1950 Cusco Earthquake: Epicenter Relocation and Focal Mechanism from Analysis of Analog Records

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Strong crustal earthquakes in the Andean Altiplano are uncommon, but occasionally damaging events occur. The 21-May-1950 Cusco earthquake damaged more than half of the buildings, causing large parts of the city to be reconstructed. Intensities reached VII MM, mostly attributed to weak adobe constructions. The poorly constrained magnitude ranges from 5.7 mb to 6 Ms. No clear surface rupture was identified, but the area of maximum intensities suggests the epicenter could be related to the normal, WNW-ESE trending Cusco fault. In 1986, another event (5.3 mb) occurred near Cusco. Aftershock studies with local temporary stations by the Instituto Geofísico del Peru (IGP) indicate the epicentral area was 5–10 km north of Cusco, associated with the SW dipping Chincheros-Qoricocha normal faults. We carried out a relative epicentral relocation of the 1950 event using station corrections based on iLOC/RSTT hypocenters of the 1986 and a few other nearby deep events of 1950. We fixed the 1986 epicenter to the IGP location, with a depth of 25 km (based on aftershock depths and pP phases at teleseismic distances). These corrections improve the rms residuals and bring the epicenter closer to the Cusco Fault, about 10 km W of Cusco city. We also use the 1950 analog seismograms (Mainka and Galitzin-Wilip) recorded at La Paz station to estimate the magnitude as 5.8 Mw. Waveform modeling of the 1950 analog seismograms shows the focal mechanism is consistent with a WNW-ESE normal fault.

## AS25-0315

# The magnetic measurements of Alexander von Humboldt

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Between 1798 and 1803 the explorer and polymath Alexander von Humboldt undertook his famous voyage of discovery to South America. Among his many diverse scientific endeavours, he made measurements of the magnetic field using a dipping needle. The record consists of 125 determinations of the inclination of the magnetic field, some of which have already been incorporated into global geomagnetic databases, and in 98 cases, the number of vibrations of the needle counted in a period of ten minutes at each station, which gives a measure of the relative intensity of the magnetic field. Here we have collated the entire catalogue of magnetic measurements. Although several of the stations lack co-ordinates, presumably when conditions prevented the use of a sextant, in all of these cases we have been able to infer the location from the field notes. Furthermore, we have uncovered sources of transcription error in those measurements already in used in field modelling and corrected them accordingly. Comparing the full set of data against predictions from the gufm geomagnetic field model, we explore possible artefacts in the data related to the stability of the instrument, and in particular consider what further information relative intensity measurements may offer concerning the geomagnetic field and its secular variation.

## AS25-0423

# Historical instrumentally-recorded M6-class earthquake in the Korean Peninsula: the 19 March 1952 Mw6.3 Suburban Pyongyang Earthquake and its seismic implications

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Historical earthquakes provide valuable information on the assessment of seismic hazard potentials, which is particularly useful for low seismicity regions. There was a magnitude 6 class earthquake in 1952 at the southwestern suburban Pyongyang, North Korea. The earthquake is the largest instrumentally-recorded event in the Korean Peninsula. Long-period analog seismic records at three far-regional and teleseismic stations are analyzed to determine the poorly constrained source parameters. A combined analysis of long-period waveform inversion, depth phase analysis, magnitude estimation, and synthetic waveform modeling enable us to cross confirm the focal depth, event magnitude, and focal mechanism. Strong ground motion simulation confirms the observed seismic seismic damage in Seoul. The event is a normal-faulting earthquake with magnitude of Mw 6.3 and focal depth of ~28 km. The long period waveform inversion suggests normal fault motions with strikes 34^o/244^o, dips 66^o/27^o, and rakes -103^o/-63^o. The peak ground motions suggest seismic damage of VIII in the modified Mercalli intensity (MMI) scale in the epicenter and V-VII in central Pyongyang. The source region may belong to the eastern margin of the paleo-collision zone between North China and South China block to develop crustal-scale seismogenic structures where mid to lower crustal events occur continuously under the current ambient stress field.

## AS25-0648

# Status and decisions about Seismic Patrimony Preservation Tutorial

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Analog seismograms and its complementary documentation contain original and highly interesting seismic data that deserve the necessary efforts to be able to both preserve and use them. Unfortunately, many collections are still in risk because of inadequate storage conditions and lack of proper recognition. At many institutions personnel and resources available are scarce and it is extremely difficult to devote part of them to improve the present situation. It is common that scientific responsibles (curators) for the collections have not direct access to basic ideas for the preservation of documents (mainly because lack of instruction).

We elaborated a tutorial mainly devoted to ease the smallest institutions to recognize their seismic patrimony and to face some minor actions or projects to improve its preservation and use. We think it can also be useful to bigger institutions as a guide for sharing initiatives towards using the limited available resources with accorded goals, standards and practices in order to maximize potential results. It provides a basic knowledge on the topic useful to explore other initiatives and access other more extensive literature without getting lost.

Here we review the scope and limitations of the present pdf version that has been completed and shared freely to the interested community and open a debate to pursue: a) selection of additional dissemination strategies to reach to as many collection curators as possible; and b) decisions on the next areas and topics to expand with new chapters and/or efforts.

## AS25-0688

# Ground motion from ancient plate boundary earthquakes in Japan

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The epicenters and magnitudes (M) of historical earthquakes in Comprehensive List of Damaging Earthquakes (List) are widely used in Japan, and their values were determined from the distribution of seismic intensities in the JMA scale and results of paleoseismology. We reconsidered the epicenter and M of the 684 plate boundary earthquake along Nankai Trough by incorporating both methods of intensity distribution and paleoseismology. We excluded two points from seven in Usami (1994, 2010), due to the limitations of their historical materials. Two ruins were chosen from the list of earthquake archaeology results in List, and were rated V+ and ≧V. The intensity distribution is similar to that of the 1946 Nankai earthquake, so we adopted its fault model by Murotani et al. (2015), and set the epicenter and depth at the model center. The fault distance from each point to the model was calculated using P4CF. The intensity at each point was computed using the distances, attenuation equation, M of List (8¼), and model center depth. We obtained 5.6 for Tosa and 5.0 to 5.5 for the others. They are consistent with those of Usami (1994, 2010).

To further confirm this, we performed ground motion simulations based on the method proposed by the Earthquake Research Committee of Japan. We plan to conduct similar reconsideration and ground motion simulation for the 887 plate boundary earthquake.

## AS25-0821

# Breathing New Life into Legacy Seismic Data: Digitization and Processing of Legacy seismic profiles from the Adriatic Sea, Central Italy

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Legacy seismic data constitute an unexploited source of geological information. Normal incidence Seismic reflection images, seismic transects, acquired in the 1960's offshore the Fano-Pesaro area (Italy) provide unique constraints on the geological structure. This extensive dataset consisting of a number or crisscrossing profiles was originally acquired for hydrocarbon exploration purposes. Unfortunately, only hard-copy paper images are currently accessible. These were scanned and digitized through WIGGLE2SEGY MATLAB script. "Cosmetic" processing including: spectral and amplitude balancing; band pass filtering; surface consistent decon; was applied to the resulting segy formatted files (stacks, migrated stacks). After these homogenization step attribute analysis was attempted to further enhance the signal quality and extract structural features. The reprocessed data provide new insights which help determine the 3D geometry of the thrust fault system. This study highlights the relevance and impact of these historical dataset for structural reconstructions. Furthermore, this research emphasizes the additional insights that legacy data can unravel to refine geological and seismic hazard models. Additionally, these costly data-sets contributes to help support ongoing initiatives focused on carbon capture and storage (CCS) in the Adriatic sea. In summary, this study underscores the importance of preserving, digitizing, and disseminating historical seismic records to ensure their accessibility for future geoscientific investigations and sustainable resource management and emphasizes the relevance for the adoption of FAIR principles and the establishment of legacy data archives.

## AS25-0830

# Tatuoca magnetic observatory magnetogram digitization and data extraction: early results

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The first magnetic observatories were built at the end of the 19th century using mechanical equipment called classical variometers to register field variations. The digitization of magnetic observatory operations started around 1970, but it was not a uniform process, and many observatories kept classical variometers in use. Therefore, there is a vast collection of magnetograms in observatories worldwide. Recently, many institutions have begun digitizing magnetograms to preserve and extract data. This work reports the progress on the digitization and data extraction process of the Tatuoca Magnetic Observatory (TTB) in Brazil by the multidisciplinary team of archivists, information scientists, computer scientists, and geophysicists. Our methodology starts with image processing steps to filter and minimize noise in the scanned magnetograms. Then, we employ machine learning algorithms to separate baselines from trace curves. We test this approach using TTB magnetograms to determine how well the algorithm distinguishes the curves in each magnetogram. Then, we compare the scanned magnetogram images to magnetograms created using the extracted data. Our results show that our algorithm can reconstruct the original magnetogram for simple cases without multiple crossings of trace lines. For these simple cases, the extraction process continues through a unit conversion to transform pixels to millimeters (distance units) and then to the appropriate magnetic units using the metadata from yearbooks. Next, we aim to improve the algorithm to distinguish line crossings efficiently. In the future, we look forward to building an artificial intelligence routine within the process to solve the efficiency problems present in other projects.

## AS25-0832

# Earthquake Records in Village Detail Registers of Sagami Province in the Kanto Region of Eastern Japan

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There is a historical document called "Village Detail Registers" (Mura-Meisaicho). These were summaries of villages that Japanese feudal lords ordered to be submitted for each village during the Edo period. Village Detail Registers written after earthquakes sometimes contain information about earthquakes and tsunamis, and some have been included in published collections of earthquake historical materials. This study investigates Village Detail Registers in Sagami Province (present-day Kanagawa Prefecture) and reports on entries related to the 1703 Genroku Kanto Earthquake and the 1707 Hoei eruption of Mount Fuji. The "Bunsei 4 (1821) Miura County Shimomiyata Village Detail Register" records topographical changes observed at Miyata Port in the Miura Peninsula (present-day Miura City) during the 1703 Genroku Kanto Earthquake. It indicates that Miyata Port became shallower due to the tsunami. This change suggests ground uplift consistent with the 1.1–1.7 meter uplift in the southern Miura Peninsula estimated from the altitude distribution of biological fossil assemblages. However, the exact height of the tsunami or amount of uplift cannot be determined from these historical materials. The "Horeki 6 (1756) March Miura County Akiya Village Submission Register" contains an entry about a landslide that occurred in Akiya (present-day Yokosuka City), and its restoration work. It appears that the same location experienced a landslide during the 1923 Kanto Earthquake as well. Additionally, many Village Detail Registers contain entries about ash fall from the Hoei eruption of Mount Fuji. These provide data that can be analyzed to understand the distribution of ash fall and resulting floods.

## AS25-0834

# Developing workflows for the vectorization of legacy seismograms

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The discovery and vectorization of legacy seismic data are two of the barriers to the (re)use of seismic data recorded on physical media. Challenges include imaging the large numbers of records, metadata discovery and curation, and the creation of time series accessible to modern digital data processing methods. Here, we describe and demonstrate progress on the development of an open source web-enabled data pipeline that aligns with FAIR practices and incorporates FDSN data exchange standards for legacy seismic data. The target data sets are the WWSSN scans from the Historical Seismogram Filming Project and new scans this project will create from the Caltech Seismological Laboratory paper records collection. The project workflow begins with creating a digital image of a seismogram. Next, the image will be uploaded to the Archiverse platform, which will extract and curate recorded station metadata, removing this information from the image. We plan to capture researcher annotations in a later stage of the project. The new image will be passed into the processing pipeline for vectorization. For this project, we build upon the open-source SKATE (https://seismo.redfish.com/#/) platform for vectorization. This open-source Python software can be used by any researcher with an internet connection or on their desktop. As the project is in its early stages, we seek input for developing a robust tool that will meet the needs of a broad range of researchers and contribute to the growing knowledge of FAIR practices in seismic legacy data curation.

## AS25-0842

# New NMSOP chapter on analog seismogram processing: present status

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The New Manual of Seismological Observatory Practice, NMSOP, is a compendium of seismological knowledge needed to run observatories and seismic networks. Also, it is intended to facilitate the use of data acquired by seismic networks. It mainly focuses on present digital data and systems. But a large amount of earthquakes were recorded in analog seismograms and young people interested in past events has no experience on how to use analog seismograms. The "know-how" about how they were recorded is being lost. This knowledge, now dispersed in old papers and reports, needs to be collected and assembled in a basic reference manual for future users, now more than ever. The CoSOI of IASPEI approved in 2023 an initiative directed to complement the NMSOP with a chapter devoted to this topic. It is intended to give to new users of analog seismograms a basic knowledge about the main characteristics of the records and help them to properly digitize them. Analog seismogram morphology, time accuracy and time corrections, instrument transfer function determination and needed trace corrections for digitization are reviewed. Further bibliography is given. The first (beta version) of this chapter, its contents and main features will be presented.

## AS25-0853

# Historical data in Geosciences: insights from the past, lessons for the future

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We are witnessing a remarkable transformation in the field of Geosciences, driven by unprecedented advancements in data acquisition and processing. This shift is particularly striking given the relatively modest theoretical progress of our time. In this lecture, we will explore several historical examples that offer valuable insights into how we might navigate this new era across various branches of Geosciences. Specifically, we will examine: (i) the geomagnetic measurements recorded by Don João de Castro in the first half of the 16th century, (ii) the earliest systematic meteorological observations in the Americas, conducted in Recife, Brazil (1640–1642) and others remarkable cases, (iii) geomagnetic observations made by Spanish and Portuguese militaries in the Pacific Ocean in the 18th century and the interior of Africa in the 19th century respectively, (iv) the first known space weather prediction in history, which took place in Spain in 1818, and (v) notable cases of geophysical data recovery in the Iberian Peninsula including seismological accounts in the 18th and 19th centuries. Through these examples, we will highlight key ideas that can illuminate our path forward in this new and dynamic scientific revolution.

## AS25-0862

# Relocating the historic Heligoland explosion using a modern locator algorithm

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On 18 April 1947 almost 4000 tons of high explosive was detonated on the island of Heligoland, located approximately 70 km from the German Mainland in the North Sea. This was a planned explosion to dispose of surplus WWII ammunition stores and was used as a seismic source for a multi-national experiment aimed at characterising crustal velocities in Northern Europe. Recordings of the seismic signals from the explosion were made at 13 permanent and 25 temporary stations (including at two vessels deployed in the North Sea) in 7 countries. The station timings used in the experiment were taken from a series of radio time signals transmitted by the B.B.C European service providing a timing accuracy of ~1s, which is approximately 3x better than the average individual timing accuracy for stations used at that time. The explosion is noted in the 1947 International Seismological Summary with associated phases from 15 stations (7 of which were not part of the original experiment). We have combined these reports, and reports from other European seismic bulletins to obtain the first seismically derived hypocentre for the Heligoland explosion and provided the most complete listing of seismic phases associated with it. This event will be the earliest added to the IASPEI Reference Event List and will provide an absolute benchmark for Northern Europe.

## AS25-0902

# Digitizing Continuous Magnetic and Electric Field Recordings from an Analogue Era

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Dedicated continuous scientific measurements of the strength and direction of the Earth's magnetic field began at Greenwich and Kew observatories in London, United Kingdom (UK), in the middle of the nineteenth century. Collimated light was focussed onto mirrors mounted on free-swinging magnetized needles which reflected onto photographic paper, allowing continuous analogue magnetograms to be recorded. Other observatories in the UK, created in the decades afterwards including Stonyhurst and Falmouth, adapted similar technology and it was used as standard up to the 1970s in the UK. Indeed, analogue systems remained in use in some institutes until recently. In addition to magnetic records, geoelectric field measurements were made in London from 1868 to 1895 before electrified railway noise became too dominant. The magnetograms were photographed between 2007 and 2013 allowing researchers to freely access the data online. However, the problem remains of how to extract significant value from the records which is hindered by the manual requirement for digitisation. We discuss research efforts thus far using machine learning and show examples of the major events that have been extracted at present.

## AS25-0936

# Discovery of Data Related to Historical Earthquakes Through an Ancient Document Deciphering Contest Utilizing Regional Historical Materials

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From October 5, 2024, to January 31, 2025, the first Ancient Document Deciphering Contest was held over a period of about four months. This was implemented as part of the collaborative efforts following the "Comprehensive Partnership and Cooperation Agreement for the Publication of Regional Materials Digital Archives" signed in September 2024 by Ina City in Nagano Prefecture, AMANE LLC, and the "Minna de Honkoku" (Collaborative Transcription) project. Under the planning of Ina City and a member of the Ina City Regional Development Cooperation Corps, the contest was realized through the publication of ancient documents from Ina City's collection on AMANE Archives operated by AMANE LLC, and their registration on "Minna de Honkoku," which enables online transcription of ancient documents. During the contest, 439 historical materials totaling 1.58 million characters were transcribed. Among the transcribed data, descriptions related to multiple earthquakes were discovered, including an earthquake that occurred in 1725, estimated to be M6–6.5. This is an example of how "Minna de Honkoku," which started in 2017 as a project to transcribe historical materials on earthquakes, has grown into a platform that helps utilize regional historical materials, and in turn, has led to the discovery of data related to historical earthquakes.

## AS25-0962

# Seismological heritage beyond borders: preservation and dissemination of early TRI station materials

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Approaching the 50th anniversary of the devastating 1976 Friuli earthquake, OGS has undertaken an effort to preserve and disseminate rare and scarcely accessible seismological materials. This heritage primarily comes from the Trieste seismic station, installed by the Austro-Hungarian empire after the Ljubljana earthquake of 1895. The station has a unique history, having operated under multiple sovereignties—Austro-Hungarian empire, then Italy, under U.S. peacekeeping forces after World War II, and Italy again in the autonomous Friuli Venezia Giulia region.

The materials retrieved—original seismic station logbooks, bulletins, paper analog seismograms, scientific correspondence, books, and reports—offer invaluable insights into early seismic monitoring and the evolution of observational techniques. By safeguarding and digitizing some fragile records, we aim to ensure their accessibility for scientific research while shedding light on the historical development of seismology across shifting geopolitical landscapes.

This initiative not only enhances our understanding of long-term seismicity but also contextualizes the institutional and scientific responses to past earthquakes, including those preceding the Friuli event. This presentation will highlight our efforts, key findings, and the significance of preserving seismological heritage in fostering international collaboration and advancing earthquake research. By integrating historical archives with modern analysis, we contribute to a broader reflection on seismic hazard and risk mitigation, particularly in the context of commemorating the 1976 Friuli earthquake.

## AS25-1006

# The 22 December 1884 North-East Atlantic earthquake

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The compilations of the earthquakes in the North-East Atlantic include an earthquake that occurred on December 22, 1884. The newspaper of the Azores, "Açoriano Oriental", reports an earthquake lasting two minutes that occurred at 2:15 am; also, the scientific journal Science reports a "terrible shock" in the vicinity of the Azores Islands and reports that the weather was fine with a light breeze. In this study, we present an analysis of macroseismic information and ship observations to locate this event and use empirical relationships to infer the earthquake's magnitude. The felt area suggests a significant magnitude event located along the Azores Gibraltar fracture zone – the western segment of the Nubia – Eurasia plate boundary. This segment of the plate boundary segment was the place of three earthquakes in the 20$^{th}$ Century: The 1939 earthquake and tsunami had its source close to the Azores, at −24.34 E, 37.17 N on the western tip of the Gloria Fault, whereas the strike-slip events of November 25 1941 and the May 26 1975 had magnitudes of about 8.3 and 7.9 respectively. In this study, we compare it with the instrumental earthquakes located along this plate boundary segment as a contribution to the area's seismic and tsunami hazard assessment.

## AS25-1011

# Bringing controlled-source seismic data to the European Plate Observing System (EPOS)

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Controlled-source seismic imaging of the lithosphere is essential for understanding landscapes, surface geology, and natural hazards at local, regional, and global scales. Numerous challenging data acquisition projects have been performed worldwide since the mid-1900's. The lack of a common archiving initiative hinders their accessibility, restricting the potential for reanalyzing using new leading-edge developments in data processing, interpretation, and modeling. The European Plate Observing System (EPOS), a pan-European distributed research infrastructure, integrates data, data products, and services for Solid Earth, offering the appropriate framework for enabling access to these data. EPOS is a virtual platform built on FAIR (Findable, Accessible, Interoperable, and Reusable) principles. Its content is defined by thematic communities using a bottom-up approach. Despite their scientific value, controlled-source seismic datasets are not yet included in EPOS.

Existing controlled-source data open-access repositories (e.g. Etsin, www.etsin.fairdata.fi, Finland, SeisDARE doi: 10.5194/essd-13-1053-2021, Spain) preserve and distribute multidisciplinary datasets. These repositories store datasets with permanent identifiers (DOI), ensuring their long-term availability and compliance with the FAIR principles. Bringing controlled-source seismic data into EPOS is currently an evolving community-driven initiative with the aim of developing an interface linking repositories and EPOS, and a discovery and information service that helps users assess the relevance of seismic datasets for (re-)use in addressing scientific questions. This is an open call to participate, contribute, and support the integration of control-source data into EPOS

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## AS25-1164

# favoring the access to numerical geodynamo data

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Since their advent in the late 1990s, numerical geodynamo simulations have raised growing interest. They were first developed to understand the physics within planetary cores, leading to the era of benchmarks and scaling laws. Today a new generation of dynamo simulations is arising, reaching more turbulent states with extreme parameters (e.g. low Ekman, low magnetic Prandtl), sometimes thanks to parameterization of subgrid processes. These numerical data products are more and more considered to assess geodynamical scenarios (e.g. torques at play, mantle control), or to analyze geomagnetic data through the construction of statistical a priori information on the core state (motions and/or magnetic field), and within data assimilation algorithms. Here we propose a web tool for exploring the pool of available numerical dynamos. Organized via diagrams function for instance of the dimensionless numbers, it gives access to the URL and/or contact from which data can be accessed. The exploration and selection of available dynamo data is channeled by tuning the ranges of parameters of interest, and/or choosing the numerical set-up (e.g. boundary conditions, forcings, etc.). This effort is developed in the context of the IAGA Division 1 FAIR-MOD working group.

## AS25-1198

# Digitizing and Archiving Paper Seismograms from the Taiwan Telemetered Seismographic Network (TTSN), 1971-1990

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The Taiwan Telemetered Seismographic Network (TTSN), established in 1972 by Academia Sinica, was the first modern digital regional seismic network in Taiwan. It consisted of short-period seismometers with a natural frequency of 1 Hz. In 1990, the Taiwan Central Weather Bureau (now the Central Weather Administration) took over its operation, improving station coverage and telecommunications to establish the new CWASN. Over its operational years, the TTSN recorded at least 15 disastrous earthquakes with magnitude (Mw) exceeding 5. Continuous waveforms were preserved using drum recorders, while significant earthquake signals were digitized from FM magnetic tapes, which functioned as a two-month ring buffer.

To support seismic hazard assessment and seismological research in Taiwan and neighboring regions, we are initiating a project to digitize and archive historical waveform data from the TTSN. These paper seismograms, stored on rolls of film, are being scanned at 600 dpi and organized into an accessible online database. We welcome collaborative efforts to advance the application and processing of this invaluable dataset.

## AS25-1238

# Preservation of legacy geophysical data in the National Geophysical Data Archive of Spain

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The National Geophysical Data Archive of Spain (located at the Geophysical Observatory of Toledo) is a centre created by the Instituto Geográfico Nacional (IGN) in 2007 to preserve all the geophysical documentation produced in all the observatories that the IGN has had in operation throughout its history.

Since 1909, analogue geophysical data (seismological, geomagnetic, geoelectric) have been produced at the 11 observatories that the IGN has operated in Spain throughout the 20th century. All this historical information has been transferred to the National Geophysical Data Archive where it is reviewed, classified, and catalogued in a database, to be finally archived in the Archive's records repository, with the appropriate conditions for its future preservation.

For the study of earthquakes recorded in the 20th century, this Archive has a large volume of information. The documents most consulted by researchers are the seismic records of the seismographs installed in the IGN Geophysical Observatories, but the Archive also houses an important collection of complementary information.

As for geomagnetism, the Archive houses all the variometric records obtained at the IGN Geophysical Observatories, but also all the base determinations and the records of the field campaigns carried out by the IGN to produce and publish the national geomagnetic maps.

In addition, the IGN is carrying out some projects to scan this historical documentation (mainly seismic records) for backup purpose and to respond to data requests received by this Archive.

The Archive also houses an exhibition of historical geophysical instruments recovered and restored at the Geophysical Observatory of Toledo.

## AS25-1297

# The Lisbon 1755 Conundrum

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Despite its prominence in historical seismology, the Lisbon earthquake of 1755 has been the object of very scarce quantitative studies. Although the quantitative tools developed near the end of the 20th century—with emphasis on the technique of Bakun and Wentworth (1997)—provided the means for a robust analysis of historical data, until recently the only published assessment of the magnitude of the 1755 earthquake was that of Johnston (1996). That study included an estimate of the magnitudes of the New Madrid earthquakes of 1811–1812 that was deemed inaccurate by multiple authors, but this did not prompt the reassessment of the proposed value of M8.7 for the 1755 earthquake, which remained mostly unchallenged. In 2020, I applied the method of Bakun and Wentworth (1997) – with adaptations required by the total lack of similar events in the region – to the wealth of historical data pertaining to the 1755 earthquake (1206 intensity datapoints from Portugal and Spain) and obtained Mi 7.7±0.5 (Fonseca, 2020). Plotting the intensity as a function of distance revealed two clusters of outliers (>2 standard deviations, not included in the estimate), amounting to 3.6% of the total dataset. The conundrum that is addressed here is this: how could an M7.7 earthquake cause the well documented level of damage in Lisbon, at a distance of the order of 250 km from the epicentral region? Also, is this result consistent with the widespread observations of tsunami inundation? This talk discusses possible solutions to this conundrum.

## AS25-1303

# A visitor's guide to the seismic hazard of the Lower Tagus Valley

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This paper proposes an alternative way to visit Lisbon and its surroundings that highlights aspects relevant to an appreciation of the seismic hazard affecting this intraplate region. Besides the earthquake-related features that are a staple of most touristic tours – such as the Carmo ruins or the Pombaline buildings of downtown Lisbon – multiple sites tell stories or at least raise questions that should not be ignored in that they constrain our assessment of the seismic history of the region. The mountain ranges of Arrábida and the broad Tagus lagoon adjacent to Lisbon document the Late Tertiary and Quaternary tectonic evolution of the Lower Tagus Valley, of which the current activity seems to be a subdued continuation as indicated by space geodesy. The Terreiro do Paço contains important clues to the seismic vulnerability of the Lisbon waterfront, ranging from the fate of the Cais da Pedra in 1755 to issues affecting Metro expansion works in the last decades. Setúbal and Cascais document the exposure of coastal cities to tsunami hazard, while the Belém area provides an acid test to the tsunami exposure of the capital. Just North of Lisbon, the Lezíria hides barely explored paleoseismic evidence of strong intraplate earthquakes, the destructiveness of which is attested by cities such as Santarém or Benavente. This paper aims to add a layer of historical seismology to sightseeing in the Greater Lisbon region.

## AS25-1386

# Creating a Historical Database: Monuments of the 1755 Lisbon Earthquake

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A historical research project has been conducted using a large volume of ancient documents, focusing on the damage to monumental buildings that occurred during the 1755 Lisbon earthquake. A database of monuments existing at the time of the earthquake has been created, primarily referencing those presented by Pereira de Sousa in 1909, 1914, and 1928. This database includes the polygons of the monuments within a GIS framework, along with bibliographic descriptions of the main geometrical properties of the buildings, the type of damage suffered during the shaking, the tsunami, and the urban fire. We also have soil characterization for each location and information about the topographic environment. More than 400 cases within the present limits of the Council of Lisbon have been recovered from early damage descriptions, with the majority located in the old city. This data, together with information from residential buildings, contains essential insights to understand the extent of damage inflicted and is of great relevance for correlating with physical characteristics such as fault rupture, wave path, and local site effects.

Although Portugal is located in a region of moderate seismic hazard and has experienced several earthquakes, events with large magnitudes have long return periods ("low probability-large impact"). Consequently, these unique historical data constitute essential information for scientific studies, which could be useful, for instance, in calibrating the model parameters used in earthquake simulators developed to estimate the damage distribution in the city.

## AS25-1430

# Uncovering Historical Geophysical Data and Model Resources and Tracking Data Usage Metrics through Science Explorer (SciX)

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The NASA-funded Science Explorer (SciX; https://www.scixplorer.org) represents a groundbreaking tool for literature, data and software discovery. Built upon the robust foundation of the Astrophysics Data System (ADS), which has powered search and discovery within the Astrophysics community for over three decades, SciX extends these capabilities to all domains under NASA's Science Mission Directorate (SMD). The six bibliographic collections maintained by SciX cover astronomy (including astrophysics, heliophysics, and planetary science, as well as the NASA-related biological and physical sciences), Earth science, and general science (with a focus on physics, applied mathematics, engineering and related disciplines that support NASA research). Overall, the system contains over 20 million records covering refereed publications plus all arXiv, ESS Open Archive, and EarthArXiv preprints, as well as supplementary literature of value to scientific research such as Ph.D. and master's theses, the National Academies reports, scientific proposals and conference abstracts. In addition to its bibliographic corpus, SciX tracks citations and usage of its records to provide advanced discovery and evaluation capabilities. This presentation is focused on our efforts to track the usage of digital resources in scientific publications by indexing geophysical data sets and numerical models that are formally cited, and through applying text mining approaches to identify historical model and data set mentions in published scientific literature. Our efforts contribute to the findability of legacy geophysical models and data sets by connecting the literature to model registries and data archives, where available, as well as providing usage metrics for credit attribution.

## J08/S23 Innovation in Geoscience Education and Outreach / Seismology at High-school Classrooms

### AS25-0065

# Geoscience Education for pupils in Nepal to reduce Seismic Risk: challenges and opportunities

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The Nepalese population is not aware of high seismic risk and research results in Geosciences, although seismic hazard and vulnerability are very high. To close the gap, we started to develop an educational seismology program in Nepal in 2017. The program currently involves 33 schools and focuses on (1) an operational low-cost seismic network in schools, and (2) training teachers and providing materials to teach earthquake-related topics. The seismometers are used for recording earthquakes and various 'learning-by-doing' activities, and the material developed is adapted to both classroom and outside school activities on earthquake knowledge, awareness, and preparation. This latter allows to reach a broad group of people, e.g. through an Earthquake Awareness Song and an earthquake preparedness card game, as well as a guide for earthquake evacuation drills in schools. Our overall approach has been very well received by teachers, students, and the local government, and the impact is measurable. However, efforts to expand the program throughout Nepal, particularly to the western region where a M8+ earthquake is expected, is challenged by very low awareness and the lack of long-term funding opportunities for our program.

We have recently initiated a collaboration with the school seismology project in Switzerland, aimed at sharing up-to-date educational resources, insights gained, and facilitating exchanges among teachers and students in the field of geoscience education which is of mutual interest. The lessons learned can be applied to enhance earthquake awareness and to reduce seismic risk in other regions at high or moderate risk.

## AS25-0166

# Enhancing cross-disciplinary research – dissemination of Geo-INQUIRE EU-project

*Mariusz Majdański*[1], *Iris Christadler*[2], *Giuseppe Puglisi*[3], *Jan Michalek*[4], *Stefanie Weege*[5], *Artur Marciniak*[6], *Sylwia Dytłow*[7], *Sara Pero*[8], *Fabrice Cotton*[5], *Angelo Strollo*[5], *Mateus Litwin Prestes*[5], *Helle Pedersen*[9], *Laurentiu Danciu*[10], *Marc Urvois*[11], *Stefano Lorito*[12], *Daniele Bailo*[13], *Otto Lange*[14], *Gaetano Festa*[15]

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The Geo-INQUIRE (Geosphere INfrastructure for QUestions into Integrated REsearch) project, supported by Horizon Europe, aims to improve geoscience research infrastructures and services to make high-level data and products available to the broad geosciences research community.

The project places great emphasis on supporting the dynamic development of data and services through the effective use of Research Infrastructures such as EPOS, EMSO, ECCSEL and ChEESE. Training, networking, and community building are the key to supporting it. The methodology ensures the strengthening of the participation of both young and experienced researchers and the inclusion of often underrepresented communities.

Project dissemination activities include a series of open online training and more specialized on-site workshops focusing on data, data products, and software solutions. Scientists, early-career scientists, and students are communities that can explore various fields of science related to the geosphere with possible connections through research infrastructures. We raise awareness on the potential and possibilities of Research Infrastructures contributing to Geo-INQUIRE, as well as data integration and the importance of FAIR principles. The training offer is constantly updated on the project website www.geo-inquire.eu.

The Equality and Diversity Panel of the project proposed two goals to reach, and engage at least 40% of females and at least 35% of participants from widening countries. Thanks to strict selection processes and transparent rules we attracted one-third female applications in nearly all training and reached 40% goal in 60% of training events.

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## AS25-0260

# Seismology in High-School Classrooms: Enhancing Education and Risk Awareness through Low-Cost Seismographs

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The incorporation of low-cost seismographs into high-school classrooms presents a transformative opportunity for science education and community engagement. These instruments which are typically used for seismic research and monitoring provide a practical way to teach basic physics, geology, and mathematics. By analysing real-time seismic data, students gain a comprehensive understanding of Earth processes, which also improve their scientific literacy and ignites an early interest in Earth sciences. This study examines how school-based seismograph networks are being implemented across different regions, highlighting case studies from ongoing global initiatives. The technological aspects of these low-cost sensors, their ease of deployment, and the curriculum integration strategies that maximize their educational impact are discussed. Additionally, it is examined how these initiatives enable students to actively participate in earthquake preparedness and risk mitigation within their communities. This study identifies best practices and challenges in sustaining these projects, including teacher training, data accessibility, and student engagement By evaluating current programs. Ultimately, this paper advocates for the establishment of a global high-school seismograph network, promoting international collaboration and a new generation of geoscientists.

## AS25-0337

# Listening to and watching the Earth's magnetic field in extreme states

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The Earth's magnetic field is invisible and imperceptible to the human body, yet it plays a vital role in sustaining life. Beyond its well-known function in navigation, it acts as a protective shield against harmful solar and cosmic radiation. The most drastic phenomena associated to the global geomagnetic field are excursions and reversals. During these events, the field is significantly weaker than in stable phases and the familiar North-South-pole structure is broken up into multiple poles across the globe. Global models of the Earth's magnetic field for these extrem events can be constructed from compilations of paleomagnetic sediment records.

To make these dramatic, planet-wide changes more accessible to a broader audience, we present audio-visual representations of the most recent excursion—the Laschamps event—and the most recent geomagnetic reversal—the Matuyama-Brunhes reversal. We find that the combination of sonification and visualization provides an intuitive and immersive experience, that can capture the attention of the general public far better than text and graphs.

## AS25-0410

# Increasing community resilience to the space weather hazard in New Zealand through public engagement and outreach about Solar Tsunamis

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New Zealand communities face many different hazards, such as earthquakes, tsunamis, floods, landslides, volcanic activity and storms. Another important hazard is space weather, in the form of Geomagnetic Storms, which can cause costly damage to electrical infrastructure and potentially extended blackouts lasting weeks or months, with significant impacts on the population. Raising awareness and increasing understanding of this hazard in the community is important so people can take appropriate action when warnings are given. The Solar Tsunamis research programme has included a range of outreach activities to engage New Zealand communities over the past five years and increase societal resilience to this hazard. Both a school engagement programme and a traveling exhibition were designed by experts at Tūhura Otago Museum, which have visited a range of locations across New Zealand, targeting primary and intermediate students, their families and the general public with evidence-based face-to-face and interactive experiences. Complementing these programmes, an animated planetarium film was developed for screenings in an inflatable dome — Waihiko and the Solar Tsunami. All these activities have integrated Māori concepts and language to connect with New Zealand's Indigenous communities. Other outreach activities have included public talks and a speaking tour by researchers on the project, an event at Parliament house in Wellington to engage policymakers and other important stakeholders, and resources developed for the project website to provide further narrative-based communications about the scientific background. Evaluating the impacts of such a wide range of activities across these diverse audiences has been a key challenge.

## AS25-0515

# IAGA connects with the public: The #askIAGA outreach project

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The #askIAGA is a public outreach project of the IAGA association selected in 2024 and funded for two years (2025–2026). This project aims to enhance public awareness of the scientific subjects covered by IAGA and connect with the community through social media platforms. The aim is twofold: share engaging material and communicate with the general public. Materials made with clear and creative graphics, simple language and examples of applications familiar to the public, facilitate the dissemination of scientific knowledge.

The IAGA consists of six divisions, covering topics from the Earth's core, mantle and crust to the atmosphere, ionosphere, magnetosphere, and solar wind. The plan is to produce a series of posts addressing selected topics of each division and post them on the IAGA's social media and outreach channels. For effective communication and active public participation, the project involves feedback and questions using the #askIAGA. The most compelling questions from the public will be turned into a second series of posts. We will present the first steps of the projects and provide a glimpse of the visual content.

## AS25-0589

# Seismic Risk Communication in Europe: Trends and Effectiveness Assessment

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Seismic risk communication has gained increasing scholarly attention, particularly in Europe, where it aligns with global disaster risk reduction frameworks such as the Sendai Framework. In our study, we analyze publication trends over time showing a growing interest in this field, likely influenced by heightened risk awareness, advancements in communication strategies, major seismic events, international policies, advocacy efforts, and shifts in research funding priorities. Of course, understanding these drivers is crucial for guiding future research and improving risk communication practices.

Despite this surge in interest, a significant gap remains in evaluating the effectiveness of seismic risk communication strategies. While many studies acknowledge the importance of assessment, actual evaluations are often inconsistent and underdeveloped. This study examines four key evaluation aspects: the methods and tools used, the timing of evaluations, and their impact on recipients. Our findings indicate that while quantitative approaches, such as surveys and questionnaires, dominate, critical factors (such as recipients' understanding of seismic hazards and the credibility of information sources) are frequently overlooked.

To enhance effectiveness, interdisciplinary collaboration is essential, integrating insights from social sciences, psychology, communication studies, and seismology. Mixed-method approaches, combining quantitative and qualitative techniques, can provide a more comprehensive evaluation. Iterative models with continuous stakeholder feedback and participatory methods, such as co-design workshops, can further refine strategies. Establishing clear evaluation criteria, drawing from best practices in other fields, will strengthen seismic risk communication, ultimately fostering a more informed and resilient public. Addressing these gaps is essential for improving disaster preparedness and reducing seismic risk impact.

## AS25-0599

# Environmental science exploration days: Breaking the barriers, and widening participation in the Scottish capital

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Subject-specific interests often start at an early age, and designing engaging outreach activities can be key to encouraging scientific interest in young learners, paving the way for future careers in science, technology, engineering, and mathematics (STEM). Furthermore, the importance of making STEM fun and accessible early on should not be underestimated; once students develop a negative perception of a subject, it can be challenging to rekindle their interest.

We designed our project with the aim to inspire school pupils from under-represented backgrounds to engage with environmental science, before they select their subjects in secondary school. We achieved this by designing and hosting 'Environmental Science Exploration Days' (ESE Days) on the university campus.

ESE Days exposed the pupils to a wide range of environment-related activities through the day, which were designed and presented by PhD students from a wide range of STEM-fields. Each 20-minute activity centres around a specific scientific question, often using an interdisciplinary approach, with a clear *hook*, *persona*, and an element of *active learning*. These all contribute to the activity being *memorable*, *exciting,* and *impactful*. Running ESE Days on the university campus immerses pupils in university life with direct exposure to the reality and diversity of the environmental sciences, while meeting role models in action.

This work outlines the format of ESE days. We present the general format for our outreach activities – including three examples from seismology, geomagnetism, and parasitology – and the philosophy behind this structure. Finally, we summarise the impact from this work.

## AS25-0684

# Australian Seismometers in Schools: a dual-purpose program for research and translation

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The Australian Seismometers in Schools (AuSIS) program launched in 2012 serves a dual purpose by integrating research and translation. It connects geoscience, education and public engagement while providing valuable seismic data to the research community. In this context, translation refers to outreach efforts that make complex geophysical concepts accessible to students, educators and the wider community.

Over the past decade, AuSIS has expanded geoscience learning opportunities particularly in rural and regional areas where students and teachers often have limited access to STEM resources. Committed to equity in geoscience education, AuSIS ensures all students regardless of location have access to high-quality hands-on learning. Many educators come from biology, chemistry, or physics backgrounds with little exposure to geoscience. By equipping 50 schools with research-grade seismometers and conducting workshops AuSIS fosters engagement with earthquakes, natural hazards, and tectonics.

As a research initiative, AuSIS strengthens seismological studies by extending the Australian National Seismograph Network particularly in rural and regional areas where seismic monitoring has been sparse. These high-quality data are used by Geoscience Australia for earthquake detection, site effect studies, hazard assessments and ground motion analysis. Seismic data from schools live stream to AusPass via SeedLink and FDSN and are accessible through AusPass and Earth Scope.

As a translation platform, AuSIS makes geoscience engaging through initiatives like the National Science Week “footquake” experiment. By bringing seismology to schools, stadiums and public events, AuSIS bridges the gap between research and public understanding and enhances Australia’s seismic monitoring.

## AS25-0726

# Aurora Nowcast

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Aurora Nowcast is a public outreach smartphone app for aurora enthusiast developed by Narwhal Aps, with collaboration with the Technical University of Denmark. One of the main features is notifications to users during intense aurora displays nearby.

Magnetometer ground stations measure the local geomagnetic condition in near-real time and give a good indication on the strength of the electrical currents in the ionosphere, that are significantly enhanced during strong auroras. Our algorithm provide location-based notifications during intense auroral displays, based on data from Iceland, Greenland, The Faroe Islands, Denmark and Norway, monitored by Iceland University, the Technical University of Denmark, and Tromsø Geophysical Observatory at UiT – the Arctic University of Norway, respectively. Additionally, it shows the position of the polar oval (based on a statistical and local model) and introduce the user to the phenomenon with illustrated information and with all-sky images from real auroral displays in southern Greenland.

The app has been designed with a privacy first philosophy in mind, it is free and without ads.

## AS25-0963

# The GEO3BCN-CSIC Educational Seismic Network; State-of-the-art and perspectives

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The GEO3BCN-CSIC educational seismic network, launched in the summer of 2019 in Catalonia (NE Spain), has a dual objective: to introduce high school students to Earth Sciences and to obtain valuable additional scientific data for ongoing research projects. We use RaspberryShake seismic stations, which allow online access to real-time data, hence facilitating student participation. The data are integrated into the large open-access RaspberryShake citizen science project.

In a first phase, most of the stations were installed in within the city of Barcelona, providing outstanding data to analyze the variations in human activity following the COVID19 lockdown. Currently, most of the stations are deployed in NE Spain, providing additional data to the EPYSIM research project investigating this area.

The obtained data allow students to observe how their building oscillates due to the seismic waves generated by local or distant earthquakes, as well as by the vibrations generated by human activity nearby, including their own movements in the center. Examples of the obtained records are posted in social networks and published in a blog to made them accessible.

Participation in the educational seismic network includes the opportunity to give a talk to students, discussing the data acquired at each center. Besides, we offer the supervision final-degree research projects based on seismic data. Future plans include consolidating the network and conducting specific training workshops for teachers.

This work has benefited from partial support of the EPYSIM Project (Ref.: PID2022-136981NB-I00).

## AS25-1062

# Outreach Activities in the GRACEFUL Project

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The GRACEFUL (GRavimetry, mAgnetism, rotation, and CorE FLow) project aimed to address challenges in understanding the Earth's deep interior, specifically the dynamics of the fluid iron-rich outer core, by combining the latest Earth's gravity field, magnetic field, and rotation observations with precise core flow models. The GRACEFUL team was committed to sharing recent discoveries with the public through various outreach activities. The GRACEFUL website (https://graceful.oma.be) features the project's main objectives, participant information, publications, presentations, workshops, awards, and the outreach efforts undertaken throughout the project. The outreach initiatives included numerous talks and open days at the Royal Observatory of Belgium and the Brussels Planetarium. Additionally, the Belgium team created a miniature model of a fluid planet to visualize the complex planetary flows, along with videos that illustrate experimental results and how fluid flow changes with varying rotation speeds. Recently, we also produced short interviews with GRACEFUL researchers to highlight key findings and upcoming challenges on social media platforms. Furthermore, a documentary showcasing the importance of deep Earth studies and recent discoveries from the GRACEFUL project is currently in development for the general public. Through these combined efforts, the GRACEFUL project not only advances scientific knowledge but also fosters public engagement and understanding of the deep Earth.

## AS25-1107

# Enhancing Seismic Awareness and Education Through the Macroseismic Sensor Network in Southern Vienna Basin

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The Macroseismic Sensor (MSS) network is a low-cost and publicly accessible seismic monitoring system deployed in the southern Vienna Basin to improve real-time earthquake awareness and education. Comprising over 50 stations, the MSS enables near real-time visualisation of ground motion data (https://www.macroseismicsensor.at), providing immediate insights into seismic events.

This initiative promotes engagement among citizens, educators, and researchers by enabling direct comparisons between perceived shaking (macroseismic intensity; EMS-98 scale[1]) and instrumentally recorded peak ground velocity (PGV). The strong public interest in earthquakes is reflected in the large number of perception reports submitted for perceptible events. Over the entire operational period of the MSS network, more than 1,000 reports have been recorded for earthquakes reaching intensity V. The data collected by the MSS network helps classify seismic events, distinguishing between tectonic earthquakes, quarry blasts, and local disturbances. Additionally, by correlating PGV with macroseismic intensity, the MSS project supports research on improving ground motion prediction equations and seismic hazard.

The network is sustained through partnerships with local stakeholders, ensuring cost-effective operations with minimal technical intervention. Users can access both past and live seismic data through an open-access platform, which promotes public involvement and scientific literacy in earthquake monitoring. We aim to highlight the educational and outreach impact of the MSS network, demonstrating how open science and digital tools can enhance accessibility, inclusivity, and community resilience in the field of seismology.

[1] Grünthal G (1998) European Macroseismic Scale 1998. Cahiers du Centre Europeen de Geodynamique et de Seismologie 15:99 pp.

## AS25-1125

# Bringing Earth Science to Life: Interactive Geophysics for Young Learners

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Early exposure to scientific topics fosters curiosity, critical thinking, and foundational STEM skills. Outreach programs that connect schoolchildren with real scientists offer hands-on experiences, demonstrating how knowledge is developed and applied. Making science interactive and accessible inspires future researchers and innovators while cultivating a lasting interest in scientific exploration, particularly in young learners. This workshop is specifically designed for schoolchildren in grades three to five, introducing them to mountain-building processes through the example of the Alps, formed by the collision of the African and European plates. Using engaging methods, students explore the geological forces shaping our planet with simplified explanations, maps, animations, and interactive research data to illustrate plate tectonics and Earth's dynamic nature.

To enhance understanding, this talk emphasizes hands-on and interactive learning. Schoolchildren engage with geological maps, cross-sections, and satellite imagery while exploring physical exhibits such as real rock samples from the Alps, crystalline structures, salt from Alpine salt mines, and an inflatable globe illustrating Earth's layers. A plate tectonics puzzle (AGU) allows pupils to reconstruct Earth's shifting landmasses, while digital animations bring scientific data to life. A demonstration table provides tactile exploration, ensuring a dynamic and memorable learning experience tailored to their age group. By integrating real-world science into the classroom at an early stage, this initiative bridges academic research with primary school education. Schoolchildren develop a deeper appreciation for Earth's processes while fostering a culture of scientific inquiry and exploration in an engaging and age-appropriate manner.

## AS25-1170

# Building an Inclusive Early-Career Scientists Network within IUGG

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The "ECSNet: The IUGG Early-Career Scientists Network" establishes a dynamic network that integrates all IUGG Associations, fostering international collaboration among emerging researchers in Earth and space sciences. Its primary objectives are to unify IUGG Associations, engage the next generation of scientists, encourage active participation among new researchers and students, and attract public interest through compelling content. We created an online platform (webpage and blog) to achieve these goals, featuring interdisciplinary topics relevant to various IUGG Associations (please see www.iugg-ecs.org). To generate content on "how to get involved," ECS representatives, association presidents, and secretaries-general collaborated to attract new members. This includes articles and videos detailing how researchers and students can join the IUGG Associations. ECS representatives also shared their experiences of how they became engaged in their respective IUGG Associations and their ongoing research. The blog posts aim to enhance ECS visibility and integrate various IUGG research areas. ECSNet also produced short movies featuring interviews with ECSs discussing their careers, experiences, and research. This platform also provides ECSs with the opportunity to engage in outreach and showcase their scientific work beyond academia. ECSNet promotes interdisciplinarity by connecting different scientific areas across various IUGG Associations, embracing diversity in terms of gender and ethnicity, and drawing in international researchers from various countries.

## AS25-1185

# Engaging Future Generations in Geothermal Energy Awareness through the TOGETHER Project

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The TOGETHER project (*Sustainable Geothermal Energy for Two Southern Italy Regions: Geophysical Resource Evaluation and Public Awareness*) integrates scientific research and educational outreach to promote the sustainable use of geothermal resources. This initiative combines geophysical resource evaluation with community engagement to foster public acceptance of geothermal energy.

A key aspect of TOGETHER is its collaboration with high schools, whose students actively participate in field activities, scientific discussions, and practical demonstrations of geophysical survey techniques, including seismic, electromagnetic, and resistivity methods. Educational outreach is designed to enhance awareness, inclusivity, and accessibility. Through interactive seminars, on-site demonstrations, and digital tools, we introduce younger generations to renewable energy challenges, fostering scientific curiosity and informed decision-making. An upcoming educational web platform will further enhance accessibility, allowing students to engage with real-time data and contribute to knowledge dissemination. The project exemplifies innovative science communication, leveraging Open Science and hands-on learning to bridge the gap between research and societal engagement. By involving students in energy transition dialogues, TOGETHER ensures that the next generation is equipped to tackle future sustainability and energy challenges. Preliminary results of the activity validation protocol will be presented.

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## AS25-1196

# Enhancing geoscience education and outreach through LiDAR-Based 3D models and virtual reality: the Lamponi grotto case study, Etna volcano

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Innovative digital tools are transforming geoscience education and outreach by Osservatorio Etneo improving accessibility, engagement, and scientific communication. This study explores the application of LiDAR technology, 3D modelling, and virtual reality (VR) in the investigation of the Lamponi Grotto, a lava tube located on the northern flank of Mount Etna. The integration of these technologies provides a novel approach to visualizing complex subsurface geological structures and their seismic response.

A high-resolution LiDAR survey was conducted to generate a detailed 3D model of the lava tube's interior and exterior morphology. The 3D model was analysed to determine roof thickness, a key parameter for future numerical modelling and structural assessments. Additionally, the model was integrated into a VR environment, creating an immersive platform for education and outreach that allows students, researchers, and the public to explore the lava tube remotely.

This approach enhances geoscience education by bridging the gap between field-based studies and digital learning. It also promotes inclusivity by making geological structures accessible to individuals who may face barriers to physical fieldwork. Additionally, the virtual environment facilitates hazard awareness and public engagement by visualizing how lava tubes influence seismic wave propagation.

By leveraging Open Science principles and digital innovations, this project demonstrates the potential of LiDAR, 3D modelling, and VR in advancing geoscience education and outreach. These tools offer a scalable and interactive method for knowledge dissemination, fostering greater public understanding of volcanic processes and underground geological features.

## AS25-1204

# Development of a School Seismic Observatory in Southeastern Sicily Using Raspberry Shake Stations

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Educational seismology plays a crucial role in raising awareness of seismic risk, especially in tectonically active regions. We present the establishment of a **School Seismic Observatory** in Southeastern Sicily, aimed at promoting real-time seismic monitoring and fostering a deeper understanding of seismology among **students and the wider community.** By engaging schools, we seek to create a ripple effect, extending earthquake awareness beyond classrooms and into society. The project, developed through a collaboration between the **INGV - Osservatorio Etneo** and the Solid Earth Geophysics lab at the **Department of Biological, Geological and Environmental Sciences of the University of Catania,** involves the deployment of **Raspberry Shake RS3D seismometers** in selected schools across **Catania, Siracusa, Modica, and Adrano.** This initiative represents a natural progression of the **Urban Seismic Observatory of Catania (OSU-CT),** established in 2019 through the **eWAS Project**, which develops cost-effective, smart monitoring solutions for **cultural heritage protection.** These efforts contribute to a **Smart City model** for assessing natural and man-made hazards in urban areas. **Raspberry Shake stations**, compact and easy to install, require only **power, internet, and a quiet environment.** They continuously record seismic signals, sharing data in real time with **schools and the scientific community**. Beyond education, this initiative strengthens **seismic monitoring**, supporting **event detection, hazard assessment, and structural health monitoring (SHM)** of school buildings. It also promotes **STEM education, citizen science, and seismic awareness**, enhancing **community preparedness** in a high-risk region. This experience underscores the **value of low-cost seismic networks** for both research and public awareness.

## AS25-1280

# Jupyter Notebooks in European Plate Observing System (EPOS) as a learning tool

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The European Plate Observing System (EPOS) addresses the problem of homogeneous access to heterogeneous digital assets in geoscience within the European tectonic plate. EPOS has been a European Research Infrastructure Consortium (ERIC) since 2018, with the goal of building long-term and sustainable infrastructure for solid Earth science. The EPOS Platform was launched into the operational phase in April 2023 and is introducing new ways for cross-disciplinary research, especially for data discovery. Currently the EPOS Platform, a metadata and semantic-driven system for integrating Data, Software and services, provides access to data and data products from ten different geoscientific areas: Seismology, Near Fault Observatories, GNSS Data and Products, Volcano Observations, Satellite Data, Geomagnetic Observations, Anthropogenic Hazards, Geological Information and Modelling, Multi-scale laboratories and Tsunami Research.

This presentation focuses on the integration of Jupyter Notebooks into EPOS through Virtual Research Environment (VRE), implemented via the SWIRRL VRE, which allows users to perform advanced processing of datasets provided already through EPOS Platform. Examples of Jupyter Notebooks covering various scientific multidisciplinary use cases introduce typical data processing workflows and visualizations for efficient use of services collected through EPOS. We present Jupyter Notebooks as a learning tool since it can encompass description of methods for data processing and code examples which can be directly explored by users and modified. Data in EPOS is integrated through web services which can be configured to retrieve data directly from the notebook. This way the data selection and access can be simplified to parameterized queries and processed by corresponding libraries.

## AS25-1288

# Geomagnetic and electromagnetic data in a landscape of multi-disciplinary research – The EPOS data platform

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Research in the geomagnetic and electromagnetic geophysics community have long benefitted from open international exchange of knowledge. Open access to data, models and codes has become increasingly important in a landscape of multi-disciplinary research questions to support societal development. Many countries have developed national research infrastructure, but the need for transnational collaboration requires special effort and innovative approaches.

EPOS, the European Plate Observing System, is a multidisciplinary, distributed research infrastructure that facilitates the integrated use of data, data products, and facilities from the solid Earth science community in Europe. Through EPOS, geomagnetic and electromagnetic data, data products and models are made freely accessible to a wide range of audiences, covering education, stakeholder interests and engagement with policy makers.

While standards and exchange platforms for geomagnetic data and models have long been supported by IAGA committees, the access to magnetotelluric data has until recently been often restricted by missing data standards, repositories and open access policies. Within the EPOS framework, a data-sharing service for MT data has now been developed.

Members of the geomagnetic and EM community in Europe work towards the realisation of not only the data access, but also the delivery of tools and training material to make geo-electromagnetic data usable, following the FAIR principles.

In this presentation we want to update on the progress made since the release of the EPOS data portal. We also want to further engage the community on what future developments are required and desirable to engage wider audiences with our science, data and vision.

## J09 Remote sensing of decadal dynamical processes of the Earth's interior

### AS25-0145

# Decoding Multi-Year Oscillations in Earth's Deep Interior Dynamics

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A recurring periodicity of approximately six to seven years has been identified in multiple facets of Earth's system, encompassing geophysical, geodynamical, and climatic processes. This phenomenon, which we term the Six-Seven-Year Oscillation (SSYO), is observable in various Earth dynamics such as fluid movement within the Earth's core, fluctuations in the geomagnetic field, irregularities in Earth's rotation, and crustal deformations. These patterns highlight the intricate coupling between Earth's deep interior and its surface. A compelling hypothesis suggests that the SSYO, observed in both the core and mantle, may be synchronized with atmospheric phenomena, implying a complex interaction across these multi-year timescales. Recent studies have emphasized the influence of deep Earth mechanisms—including core fluid dynamics, core-mantle interactions, and mantle rotation—in driving the SSYO. In this work, realized in the frame the frame of the GRACEFUL ERC project, we present geophysical evidence, including measurements from the magnetic field, gravity field, and length-of-day data, to support the existence of these oscillations. These findings deepen our understanding of the interconnected processes that govern Earth's complex and dynamic behavior.

## AS25-0487

# Geomagnetic jerks as a product of core-surface flow acceleration pulses

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Geomagnetic jerks are the fastest variations we observe in secular variation (SV) of the internal geomagnetic field. They have been deemed spatiotemporally unpredictable, and thus make it difficult to forecast magnetic field changes. Recent core surface flow-inversions of satellite SV data show that pulses in modelled azimuthal flow acceleration are contemporaneous with localised low latitude jerks observed in the Atlantic and Pacific from 2000—2024.

In order to explore to what extent such pulses might be responsible for observed geomagnetic jerks, we simulate them with synthetic flow models. We use a Fisher–Von Mises probability distribution to spatially define the pulse, which ensures that its spherical harmonic expansion in terms of poloidal and toroidal spherical harmonic coefficients converges. To recover a dynamic flow, we add uncorrelated noise to these toroidal and poloidal acceleration coefficients. After this, we obtain SV from flow acceleration using the diffusionless induction equation, investigating a variety of background flows and core-surface magnetic field structures with our flow-acceleration pulse. Finally, we plot the expected SV at the Earth's surface.

We successfully generate geomagnetic jerks, similar to those observed by CHAMP in the Atlantic in 2003.5 and 2007, and Swarm in the Pacific in 2017 and 2020. This pulse-like simulator for low-latitude jerks is in agreement with results from numerical dynamo simulations, which suggest that jerks originate from Alfvén wave packets emitted from the inner-outer core boundary. Our results further suggest that there is no need for waves longitudinally propagating at the core-surface for jerks to occur.

## AS25-0501

# The magnetic field of the outer core: using data assimilation to understand the geodynamo

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The main magnetic field of the Earth is generated by fluid motion in the planet's outer core (geodynamo) and varies on a range of timescales. The geodynamo provides the background magnetic field of the Earth's immediate, space weather environment and is also believed to influence geodetic observables such as length-of-day variations and polar motion. Satellite-based observations of the magnetic field have provided a new level of temporal and spatial resolution. While the Earth's outer core cannot be directly observed, variations in the magnetic field provide a unique opportunity to understand the geodynamo and its relation to the rest of the Earth system.

Data assimilation (DA) has seen growing interest as a tool for making inferences about the geodynamo, from magnetic field observations. In DA, observations are merged with dynamic models, to constrain the state of a system and/or provide initial conditions for forecasts. For example, DA can be used to combine information about the Earth's magnetic field, with numerical models of the geodynamo, to constrain the unobserved fluid flow and magnetic field within the outer core.

In this presentation, we provide an overview of efforts that have been made in applying DA to the study of the geodynamo. Such work has made use of dynamic models ranging from simplified 2-D flow at the top of the outer core, to full 3-D numerical dynamo models. We conclude by providing recent results with our own geodynamo-based DA system.

## AS25-0526

# Fast waves in the Earth's core over the last 25 years inferred from satellite and ground secular variation data

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A number of recent studies, based purely on geomagnetic secular variation (SV) data, on numerical geodynamo simulations, or with data assimilation in computational models, have identified low latitude waves at the Earth's core surface, suggested to be magneto-Coriolis modes. Their power is concentrated in low azimuthal wavenumbers, primarily westward propagating at speeds of ~1500 km/yr, with periods ~7 years. We present results of inversions for core surface flow over the last 25 years, during most of which high quality measurements of the magnetic field from space are available, using ground and satellite estimates best representing core SV. Satellite data are represented by geomagnetic virtual observatories (GVOs), evenly spaced points at satellite altitude at which time series of the field components are derived from data collected in a cylinder surrounding the GVO, mimicking those produced by ground geomagnetic observatories. We input GVO vector field and spatial gradient SV values. Our inversions are regularised spatially and temporally using a number of different constraints. We obtain a good fit to the data, including reproducing signatures of geomagnetic jerks. The flows obtained with different choices of spatial regularisation are difficult to distinguish by eye, but differences emerge in their accelerations, calculated from first differences of the velocity, without any smoothing. Low latitude, fast waves are visible in time-longitude plots of azimuthal acceleration during the Swarm era, but throughout the period of study in plots of power spectral density. Acceleration pulses coincide with dates and locations of geomagnetic jerks, suggesting a causative relationship between them.

## AS25-0592

# Geodetic constraints on sub-decadal dynamical processes of the Earth's deep interior

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The Earth's interior layers -comprising the solid inner core, the fluid outer core, and the mantle- possess their own dynamical properties. These layers interact with one another, creating complex signatures in observations at the Earth's surface. These signatures are often challenging to interpret, particularly due to the difficulty of distinguishing them from surface processes. In this work, we present a partial review of recent findings that highlight the interactions between the inner core, outer core, and mantle, as revealed by sub-decadal variations in Earth's orientation parameters and time-variable gravity.

We focus primarily on two key interactions: (1) those between the fluid outer core and the mantle, and (2) those between the inner core and the mantle. These interactions influence geodetic observables such as Earth's length of day and gravity field. Conversely, we also show how geodetic observations can be used to constrain the coupling mechanisms between the core (both inner and outer) and the mantle.

## AS25-0685

# On the mantle-inner core graviational system and the lower mantle structures

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Gravitational coupling between the mantle and the inner core, manifested as oscillations in the variation of the length of day, provides key insights into the mass distribution within the lower mantle—particularly the core-mantle boundary (CMB) topography and the large low-velocity provinces (LLVPs) observed in seismic tomography models. Using a multipole expansion approach, we formulate this gravitational coupling and demonstrate that it depends on the degree-2, order-2 multipole moment of the mantle. This moment is more sensitive to the lower mantle, complementing the conventional Stokes coefficients used to describe the gravity field at Earth's surface. To further constrain the density anomalies associated with LLVPs, we examine their relationship with CMB topography through isostasy theory.

## AS25-0740

# Annual-scale variability in both the rotation rate and near surface of Earth's inner core

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The inner core has been inferred to change its rotation rate or shape over years to decades since the discovery of temporal variability in seismic waves from repeating earthquakes that travelled through the inner core. Recent work confirmed that the inner core rotated faster and then slower than the rest of Earth in the last few decades; this work analysed inner-core-traversing (PKIKP) seismic waves recorded by the Eielson (ILAR) and Yellowknife (YKA) arrays in northern North America from 121 repeating earthquake pairs between 1991 and 2023 in the South Sandwich Islands. Here we extend this set of repeating earthquakes and compare pairs at times when the inner core re-occupied the same position, revealing non-rotational changes at YKA but not ILAR between 2004 and 2008. We propose that these changes originate in the shallow inner core, and so affect the inner-core-grazing YKA ray paths more than the deeper-bottoming ray paths to ILAR. We thus resolve the long-standing debate on whether temporal variability in PKIKP waves results from rotation or more local action near the inner-core boundary: it is tentatively both. The changes near the inner-core boundary most likely result from viscous deformation driven by coupling between boundary topography and mantle density anomalies or traction on the inner core from outer-core convection.

## AS25-0766

# The nature of the torque on the mantle causing multi-decadal changes in length of day

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Changes in the length of day (ΔLOD) on decadal timescales are caused dominantly by an exchange of angular momentum between the core and the mantle. This inference is based on core surface flows inverted from the geomagnetic data; when assuming that the zonal azimuthal flows extend rigidly along the rotation axis inside the core, the changes in core angular momentum match well those required to explain the decadal ΔLOD. However, the nature of the torque between the core and mantle that transfers this angular momentum remains unclear. Here, we show that a combination of gravitational torque (reconstructed from the seismically inferred changes in the inner core rotation) and electromagnetic (EM) torque at the core-mantle boundary (reconstructed from core flows) can reproduce the observed multi-decadal ΔLOD. Using a Monte-Carlo approach, we find that optimal ΔLOD predictions occur when the gravitational coupling constant is within $1\times10^{19} < \Gamma < 4\times10^{19}$ N m, the inner core viscous relaxation time is below 20 years and the conductance at the base of the mantle is under $3\times10^{8}$ S, yielding a gravitational torque approximately four times larger than the EM torque. Our results confirm that both the bulk of the inner core (through its global rotation) and its topography (through its viscous re-alignment with mantle mass anomalies) change over multi-decadal timescales, consistent with seismic observations. Furthermore, our estimate of Γ place a constraint on the amplitude of the mass anomalies associated with Large Low Seismic Velocity Provinces residing at the bottom of the mantle.

## AS25-0900

# Planetary forcing on seismic activity: a global-scale perspective over the last 124 years

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The apparent randomness of earthquakes remains a fundamental question in geophysics. To address this issue, we investigate the temporal variability of global seismicity over the past 124 years and explore potential geophysical drivers. We construct an averaged global seismicity curve for earthquakes of magnitude ≥6 since 1900 and apply Singular Spectrum Analysis to extract dominant pseudo-cycles. These are then compared with two global geophysical parameters associated with Earth's tides: length-of-day variations and sea-level changes. Our results reveal that seismicity, length-of-day variations, and sea-level fluctuations share up to seven periodic components, largely aligned with planetary ephemerides: 1 year, 3.4 years (Quasi-Biennial Oscillation), ~11 years, ~14 years, ~19 years (lunar nodal cycle), ~33 years, and ~60 years. These findings are discussed within Laplace's tidal theory, with a particular focus on the phase relationships between seismicity and geophysical oscillations. We propose a trigger mechanism based on solid Earth–hydrosphere interactions, emphasizing the role of water-rock coupling in modulating earthquake occurrence. This study provides new insights into the external forcing of seismicity, suggesting that long-term orbital moments of Jovian planets and hydrospheric processes may play a significant role in shaping the temporal distribution of large earthquakes.

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## AS25-0954

# Geocenter excited by the solid inner core translational motion derived from geomagnetic data assimilation, LEO GPS and mass loading models

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The Earth's inner core moves relative to the solid mantle driven by the pressure and Lorentz forces on the inner core boundary (ICB), and the gravitational restoring forcing arising from the departure of the inner core from its gravitational equilibrium position. This relative motion leads to changes between the center of mass and the center of the figure of the solid Earth. To estimate the pressure force and the Lorentz force on the ICB, we assimilated geomagnetic observations in the past 120 years with our numerical geodynamo models. The gravitational restoring force is estimated based on the density differences across the ICB from PREM. These time-varying forces, together with the initial conditions derived from the difference between the geocenter locations estimated through GPS and those from the non-tidal mass loading models, are used to generate the geocenter time series excited by the inner core translational motion. The magnitude of the geocenter is on the order of 1 to 2 mm (after removing the secular trends), and are comparable to those excited by oceans and terrestrial water storage derived from MERRA2 and ERA5-land.

## AS25-1203

# Inner core rotation in a resonating Earth system with multidecadal periodicity

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Inner core differential rotation is an important but as-of-yet enigmatic component of the core dynamics and core-mantle interactions. It has been postulated by geodynamic studies and subsequently supported by numerous seismic observations, which detected inner-core temporal changes using nearly collocated repeating earthquakes or nuclear blasts. In our recent systematic search for the inner-core temporal changes using global repeating earthquakes over the past three decades, we found that all previously identified paths with significant change have exhibited little change since 2009. The consistent global pattern suggests that the inner core rotates as a whole and the rotation has been slowed. We further expanded the temporal coverage using analog seismic records back to the early 1960s. With the extended dataset, we found that the recently slowed rotation appears to be associated with a gradual reversal as a part of a seven-decade oscillation with another turning point in the early 1970s. The multidecadal periodicity coincides with changes in several other geophysical observations, including the length of day (LOD), magnetic field, and global climate system (mean temperature and sea level rise), pointing to a resonating and coupling earth system. The observed angular position of the inner core is generally in phase with the reversed multidecadal LOD variations, as predicted by previous studies with the model of mantle-inner core gravitational coupling. Our observation thus provides important constraints to geodynamo models and the core-mantle coupling, and offers the first evidence of dynamic interactions between the Earth's layers from the deepest interior to the surface.

# J10 The influence of the thermal state of the lithosphere on the tectonic processes: insights from heat-flow data and implications for geothermal resources

## AS25-0224

## The role of Heat Flow observations in constraining lithospheric deformation at the Mendocino Triple Junction plate boundary transition

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The Mendocino triple junction (MTJ) in northern California (USA) represents a fundamental plate boundary transition from the Cascadia subduction boundary (in advance of the MTJ) to the San Andreas transform boundary (post-MTJ). It is a tectonically active region with substantial earthquake activity, high uplift and erosion rates, and a complex network of active faults. As part of a San Andreas fault strength project (starting in the 1970's) the USGS measured crustal thermal conditions along the San Andreas plate boundary. Those heat flow data (>100 H.F. sites were measured) can now used to constrain the thermal evolution of the North American crust after MTJ passage. Consistent with other geophysical data and new models of plate boundary evolution, the heat flow data define two distinct thermal-tectonic corridors along the San Andreas plate boundary—a coastal corridor (Pioneer), and an adjacent inland corridor (Mendocino Crustal Conveyor - MCC). The pattern of heat flow variation differs between these two corridors with high heat flow observed immediately south of the MTJ in the Pioneer Corridor, while the heat flow pattern within the MCC Corridor rises more slowly reaching peak values ~ 100+ km south of the MTJ (equivalent to 2–3 million years after MTJ passage). In concert with low-T thermochronology, the heat flow data allow us to develop and validate detailed models of crustal thickening, uplift and exhumation within the two corridor, providing new insight into the tectonics of this fundamental plate boundary transition.

## AS25-0239

# The geothermal fingerprint of different plate-tectonic settings

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The convergence of tectonic plates as well as their rifting creates characteristic geophysical configurations with specific lithosphere and crustal thicknesses, as well as sediment cover distributions. Based on structural models integrating geoscientific observations we assess the effects of these configurations on the conductive thermal field. We use lithology-related thermal properties to parametrize 3D FE simulations of the thermal field with the FEMcode GOLEM. Though distributions of physical properties vary for different plate-tectonic configurations, we find three main factors that dominantly control the deep geothermal field characteristics: (1) the thermal lithosphere thickness that controls the average geothermal gradient, (2) the contributions of radiogenic heat to the heat budget in response to variable crustal thickness and composition and (3) the distribution of thermal conductivities -and in particular the presence or absence of insulating sediments. Depending on the setting, specific 3D thermal fields evolve that in turn control the local rheology and deformation. Rifts can be hot or cold depending on the rifting mode, intensity and age. Passive margins can be hotter on their oceanic or their continental side depending on the age of the adjacent ocean. Orogens always have a hotter crust than their forelands at the same depth in response to the topographic effect superposed with the effect of a thickened radiogenic crust. This explains the lacking deep crustal seismicity in many orogens. We demonstrate how data integrated thermal simulations predict the deep thermal configuration beyond the initial data base and provide physically motivated explanations of seismicity's lateral and depth distribution.

## AS25-0339

# Can cooling models of the ocean lithosphere account for heat flow and subsidence in the Tyrrhenian back-arc basin?

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Active seafloor spreading observed in some marginal and back-arc basins supports the hypothesis that their geodynamic evolution and lithospheric thermal structure are comparable to those of oceanic plates. Since the 1980s, it has been suggested that the relationship between heat flow and age in back-arc basins follows the same pattern observed in oceanic lithosphere formed at mid-ocean ridges. It was also argued that the seafloor depth increases with age, but unlike the major oceans, a subsidence excess of approximately 1 km was generally observed in back-arc basins. In this paper, we reviewed the heat-flow database of the Tyrrhenian back-arc basin, located in the central Mediterranean Sea, and analysed it along with seafloor subsidence. Determining the conductive heat flow in this basin has been particularly challenging due to buried, high-conductivity salt structures and localized hydrothermal activity associated with seafloor reliefs often consisting of active volcanoes. We conducted a critical assessment of thermal measurements and corrected heat-flow data for sedimentation and climatic changes in order to infer the purely conductive terrestrial heat flow. Although heat flow shows considerable variability, we can generally observe an increase from the older (Magnaghi–Vavilov) to the younger (Marsili) subbasin. Finally, we analyse the thermal pattern and seafloor depth in relation to modern oceanic cooling models derived from global heat flow and bathymetric data gathered from oceanic, marginal, and back-arc basins.

## AS25-0375

# Spatial variations in thermophysical properties of major rocks in Central Indian Tectonic Zone: Implications for geothermal potential and geodynamic evolution

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Geothermal energy is a clean and renewable resource that harnesses the heat from the Earth's interior to use both for industrial and household purposes. The Central Indian Tectonic Zone (CITZ) is recognized as one of India's ten identified geothermal provinces, hosting three prominent geothermal manifestations: Tattapani, Tantloi, and Bakreswar. The CITZ is a 400-km-wide, 1000-km-long, ENE-WSW trending orogenic belt bounded by SNNF and CIS and comprises of granites and associated plutonic rocks, lensoidal bodies of granulites, and three important supracrustal belts viz. Mahakoshal, Betul, and Sausar belts, separated by SNSF and TAN.

For the first time, systematic measurements of thermal conductivity and radiogenic heat production have been carried out in the laboratory on alkali granite, ultrapotassic granite, granitic/migmatite/dioritic gneiss/TTG gneisses, collected from the Mahakoshal and Betul belts. Prior to thermal investigations, the rocks were characterized by physical (density, porosity), geochemical, and petrographic studies.

The results indicate that most of the rocks exhibit the highest thermal conductivity (3.3–3.9 W/m/K) between SNNF and SNSF, with intermediate values (3.2–3.3 W/m/K) north of SNNF and the lowest values south of SNSF (2.1–3.0 W/m/K). Further, from west to east, average radiogenic heat production increases for alkali granite but decreases for granite and ultra-potassic granite. The distinct thermal and physical properties indicate that the granites were emplaced in multiple events, both temporally and spatially. This study provides new constraints on the thermal structure, enhances understanding of the geodynamic evolution, and establishes a critical framework for future geothermal resource assessments in the CITZ.

## AS25-0434

# High heat flow in Pranhita-Godavari Gondwana basin, India: Implications for geothermal energy exploration

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Heat flow is a key factor for understanding temperature distribution within the basin and assessing potential regions for geothermal energy. The Pranhita-Godavari Basin, one of India's largest Gondwana basins, developed within a zone of crustal weakness between the Dharwar and Bastar Cratons due to extensional tectonic activity. It is categorized into four sub-basins: Godavari, Kothagudem, Chintalapudi, and Krishna-Godavari. Temperature measurements were carried out in the basin from eight boreholes, each ~1000 m, from the southeastern part of Godavari sub-basin and three boreholes, 400–600 m, from the southwestern part of Kothagudem and Chintalapudi sub-basins.

The thermal conductivity of the borehole rocks measured by the steady-state method on 123 samples indicates that shale with coal, shale, and siltstone exhibit relatively low values (1.7–2.3 $Wm^{-1}K^{-1}$), while sandstone and phyllite have slightly higher values (2.8–2.9 $Wm^{-1}K^{-1}$), and quartzites have the highest (4.6 $Wm^{-1}K^{-1}$).

Integrating present and previous data reveal a spatial variation in heat flow within the basin. In the Godavari sub-basin, the south-eastern region exhibits higher heat flow (101–117 $mWm^{-2}$) than the southwestern region (44–84 $mWm^{-2}$). A similar trend is observed in the Chintalapudi sub-basin, with higher values in the southeastern part (104 $mWm^{-2}$) than in the southwestern part (65–93 $mWm^{-2}$). In the Kothagudem sub-basin, it ranges from 46–66 $mWm^{-2}$.

Considering the entire basin, heat flow is consistently higher in the southeastern part compared to the southwestern part. This disparity could be attributed to deep-seated tectonic activity, fault structures, and high radiogenic heat-production of the basement rocks.

## AS25-0460

# Review of existing thermal data in Bulgaria: discussion and analysis

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This study provides an overview of research on Bulgaria's geothermal potential. With current energy policies focused on reducing emissions, ensuring energy independence, and promoting renewable resources, geothermal energy is becoming an important sustainable solution.

Bulgaria's thermal field is influenced by its complex geological and tectonic structure, with heat flow values ranging from 60 to 80 mW/m² and localized anomalies above the national average. The country is divided into three main geothermal regions: the Low Danubian Artesian Basin, the Intermediate Zone, and the Rila-Rhodope Massif, each exhibiting distinct thermal characteristics.

Geothermal gradients vary from 2.4 °C/100 m in sedimentary basins to over 10 °C/100 m in tectonically active regions. Borehole temperature-depth profiles reveal thermal anomalies linked to deep fault zones and magmatic intrusions, with the highest recorded temperatures reaching 98 °C at several kilometers depth.

Recent geophysical studies, including magnetotelluric (MT) and gravimetric surveys, have provided valuable insights into geothermal heat sources. MT measurements identified deep conductive zones, particularly in the Polyanovo area, with low resistivity values indicating conductive sediments. Gravimetric data showed variations in subsurface density, associated with tectonic faults influencing heat distribution. Temperature mapping in wells up to 500 m deep confirmed thermal anomalies and the role of structural discontinuities in heat redistribution.

Despite its potential, Bulgaria's geothermal energy use remains limited. Ongoing research, including a large-scale geothermal survey project in the Sofia Basin, continues to explore promising regions for future development.

## AS25-0590

# More data and analysis of the heat flow density values in mainland Portugal

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Located in the western border of Europe, the Portuguese mainland territory has been affected by the opening of the Atlantic Ocean and by the collision of the African and Iberian plates. Compressive events in the region gives rise to formations with nearly zero porosity and many faults and fractures in the territory. Several magmatic formations with dated ages between 60 and 100 million years shows that the region has_been reheated. We can also found in the region salt formations that alter the temperature and radioactive content in the region.

The studies of the natural radioactivity of rocks shows high values in granites of the Central and Northwestern part of the territory but also in the Monchique massif located in the Southern part of the country. The relation between the last tectonothermal event and the heat flow value may be used to obtain the values found, but in addition we can speak about the low values of porosity and the ore traces (sometimes visible only with microscope) to explain the high thermal conductivity values measured. In addition to radioactive sources it is possible to find in some parts of the country exothermic chemical reactions that contribute to high thermal gradient values. Near the southern border of the territory it is possible to find, in the Cadiz Gulf, oceanic crust with relatively low values of heat flow compared to those obtained offshore in the continental border.

## AS25-0622

# Advancing Global Marine Heat Flow Data: Challenges, Insights, and the Path Forward

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The International Heat Flow Commission (IHFC) has long been dedicated to curating the Global Heat Flow Database (GHFDB), ensuring its accuracy and usability for the scientific community. With dataset now completed for many continents; efforts have shifted toward assessing marine heat-flow data. This transition presents unique challenges due to the diverse measurement techniques, environmental influences, and data quality variations inherent in oceanic settings. A significant advancement is the introduction of a novel quality score—integrating quantified uncertainty, methodological rigor, and the influence of overriding environmental effects—now applied for the first time to marine data. This framework enables a more transparent and standardized evaluation, effectively identifying gaps and inconsistencies. Looking ahead, ongoing efforts aim to refine reporting standards and enhance data accessibility, ensuring that the marine heat-flow dataset meets the highest scientific standards. This presentation will highlight key advancements, challenges encountered, and the future outlook for improving the quality and usability of marine heat-flow data within the GHFD framework.

## AS25-0638

# The First Asian Heat Flow Compilation: Quality-Controlled Data for an extended analysis of the thermal structure

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Accurate and well-documented heat-flow data is essential for exploring geothermal resources as well as for understanding geodynamic processes. The Asian continent, as the largest on our planet, offers complex tectonic settings, presenting both challenges and opportunities for heat-flow studies. In this study, we present, for the first time, a new quality-controlled and extended dataset of continental heat flow data from Asia. This subset of the Global Heat Flow Database (GHFDB) follows the metadata and quality evaluation standards proposed by the International Heat Flow Commission (IHFC). The new Asian heat flow database includes approximately 13,200 data points reported between 1947 and 2025 and collected from 360 research papers, reports, and books. Quality control is conducted through a multi-dimensional approach, assessing numerical uncertainty, methodological reliability, and environmental site perturbations. The application of this approach is based on the detailed assessment of the original literature by a large multi-national collaborative network of geoscientists. By addressing these aspects, we aim to establish a robust dataset that enhances our understanding of the thermal structure and geothermal resource potential of the Asian continent.

## AS25-0656

# An Interdisciplinary Attempt to Construct a Stochastic Crustal Composition Model for Improving the Thermal Structure

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The heat production by radioactive elements is one of the key factors in the interpretation of heat flow data. However, the data of crustal radioactivity are limited due to the spatially-limited coverage and the inaccessibility of rock samples from depth. Geoneutrinos, antineutrinos from radioactive decays of uranium (U) and thorium (Th) inside the earth, are direct observational data, and its flux has been determined with high precision by the KamLAND detector in Kamioka, Japan. Despite the high accuracy of the KamLAND geoneutrino observation, it has not been possible to validate the whole solid Earth compositional model due to the large uncertainty of the estimated crustal geoneutrino flux from the crust. We found that U and Th are localized heterogeneously at the single sample scale, and that sample-scale dispersion is dominant. Based on the results of multiple analyses, including direct observation of radioactive decay using photographic film, we are constructing a statistical model to describe the sample size effect.

## AS25-0662

# 3-D thermal structure and dehydration near the Chile Triple Junction and its relation to slab window, tectonic tremors, and volcanoes

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The southern Chile subduction zone is a complex tectonic environment, where the Chile Ridge, the Nazca (NZ) and Antarctic (AN) plates subduct underneath the South American (SA) plate. The intersection between the NZ, AN and SA plates is referred to as the Chile Triple Junction (CTJ). In this region, a gap, referred to as a slab window, has been formed between the NZ and AN slabs due to the divergence in their plate motion velocities, with volcanoes existing mainly above the subducted NZ and AN plates. In this study, we constructed a three-dimensional thermomechanical model associated with simultaneous subduction of the NZ and AN plates near the CTJ. The results show that the current temperature distributions on the upper surface of the slabs are higher closer to the Chile Ridge, and the AN plate has a distribution of elevated temperatures relative to the NZ plate at the same depth due to the northward migration of the CTJ and the slower convergence rate of the AN plate. Moreover, we calculated the water content and dehydration gradient from the temperature distribution near the upper surface of the slab and discussed their relationship to the distribution of volcanoes. In the northern part of the model domain, high dehydration gradients were obtained below the volcanic chain. Therefore, we suggest that the water released from the slab decreased the melting point of the mantle wedge just above the slab and produced melts, which may have contributed to form the overlying volcanoes.

## AS25-0665

# Machine learning-based identification of geothermal reservoirs in the northern Gulf of California, Mexico

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The northern Gulf of California (GOC) is a prime setting for investigating the interplay between lithospheric thinning, faulting, and heat transport. In this study, we use machine learning to evaluate the relationship between structural complexity and heat flow distribution, identifying prospective geothermal reservoirs. Using a Random Forest Regression algorithm trained on 2D seismic data and surface heat flow measurements, we predict heat dissipation rates across the fault systems of the northern GOC. The model explains 75% of the heat flow variance but underestimates values in highly fractured zones due to response saturation at ~1000 mW/m². Three geothermal prospects are identified, with the Mid-Gulf Thermal Anomaly as the most favorable, capable of dissipating up to 1.4 GWt of geothermal energy. Two additional reservoirs along passive faults on the Sonora margin could contribute another 2.8 GWt, although direct heat flow data is needed for validation. Our results highlight the role of fault-controlled heat advection in shaping the lithosphere's thermal state and emphasize the northern GOC's geothermal potential. These findings contribute to understanding heat transfer mechanisms in extensional settings and their implications for geothermal resource assessment.

## AS25-0681

# Enhanced probabilistic joint inversion: Integrating magnetotelluric data with multi-geophysical observations for subsurface structure imaging

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In this study, we investigate the physical properties of rocks in Earth's interior—such as temperature, density, and water content—which are fundamental for understanding regional geology and Earth dynamics. Variations in rock microstructure and subsurface conditions alter macroscopic geophysical parameters (e.g., resistivity, seismic wave velocity), and high-temperature, high-pressure experimental petrology provides essential constraints linking these properties to geophysical observations. Although previous studies have primarily relied on magnetotelluric (MT) and seismic data for geophysical inversion and used empirical relationships to estimate key parameters, limitations in vertical resolution, inversion nonuniqueness, and differing observational sensitivities hinder accurate resolution of subsurface thermal states and composition. Thus, integrating multiple datasets—including seismic velocities, terrestrial heat flow, geochemical analyses, and experimental petrology—is critical for constraining subsurface thermo-chemical structure.

MT methods, with their high sensitivity to fluids (e.g., melts, saline fluids), reveal distributions of temperature, composition, and fluids within the Earth, playing a key role in studies of mantle dynamics and lithospheric evolution. Here, we develop a self-consistent thermo-chemical joint inversion algorithm based on a Bayesian probabilistic framework. Using a Markov chain Monte Carlo approach, the method iteratively refines inversion models by combining MT data with other observational constraints while quantifying uncertainties via probability density functions. Synthetic model tests demonstrate high sensitivity to water content and temperature, and application to mid-northern United States field data shows excellent agreement between derived and measured geochemical parameters, confirming the reliability of our approach.

## AS25-0692

# A Global Heat Flow Data Revolution: Standardization, Quality Assessment, and Future Perspectives

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Over the past five years, the International Heat Flow Commission (IHFC) of IASPEI has led a transformative initiative to improve the quality, accessibility, and usability of global heat flow data. This presentation documents the collaborative efforts of the international geoscience community to establish a quality-controlled and authenticated global database of heat flow values and related thermal data, serving as an essential resource for solid Earth research worldwide.

This presentation highlights and celebrates the collaborative achievements of the global geoscience community in building a quality-controlled and reliable heat flow database. These efforts include the standardization of data formats and metadata structures to ensure consistency and interoperability, the meticulous screening of over 2,000 heat flow publications to enhance data reliability, and the development of an open-access research portal to foster global knowledge exchange.

Beyond these advancements, the presentation will explore future strategies to further expand and enhance the Global Heat Flow Database (GHFDB). It will address key topics such as improving interoperability with other geoscientific data infrastructures, integrating advanced analytical tools, and establishing structured data publication services to ensure long-term sustainability. By highlighting these scientific and technical breakthroughs, the talk aims to trigger new collaborations and partnerships, fostering the continued growth of heat flow research in the coming years.

## AS25-0694

# Establishing a New Borehole Thermal Data Scheme for Climate Studies

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The transformation and re-evaluation of the Global Heat Flow Database (GHFDB) of the International Heat Flow Commission (IHFC) of the IASPEI is ongoing since 2021. Based on these experiences, we are developing now a quality-oriented thermal database scheme to reveal and constrain past and recent changes in climate conditions from temperature data. The thermal data compiled in this part of the GHFDB will improve our understanding of the thermal impact of interactions at the lithosphere-cryosphere-atmosphere interfaces on the temperature distribution in the subsurface over time. For this purpose, high-quality continuous temperature data from boreholes are needed. Based on our recent experience in developing new standards and implementing them within the GHFDB, we are in the process of defining and describing (meta-) database fields, collecting and re-evaluating globally available temperature data from the subsurface. This process continues earlier IHFC attempts to maintain a global database for borehole temperatures and climate reconstructions. The overarching goal of this collaborative effort is to provide high-quality data sets with continuous temperature and thermal property profiles together with well-defined metadata fields to enable climate studies at different levels and for different scales. In addition to temperature, the dataset should also include information on the measuring date, the lithology, stratigraphy, and thermal properties of the drilled sequence, based on an appropriate resolution and provided as open-access publications. Initial examples from German data are presented, which can serve as a template for further evaluation of thermal background data for future analyses.

## AS25-0749

# Effect of recent warming on thermal regime of a shallow subsurface: a case study from Caravelinha station in south-central Portugal

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We present results of geothermal measurements carried out in a 200 m deep borehole (Caravelinha borehole) near the town of Evora in south-central Portugal (38° 36.0' N, 7° 54.6' W, 330 m a.s.l.). The research consisted in repeated temperature logging in the period 1997–2017 complemented by a long-term temperature monitoring of air (0.05 and 2 m above ground), soil (at depths of 0.02, 0.05, 0.1, 0.2, 0.5 and 1 m) and bedrock temperatures (at depths of 1, 2.5, 5, 10, 20, 30 and 40 m) in the period 2005–2024. The observed temperature-depth profiles indicate downward propagating warming of the subsurface that lowers substantially the terrestrial heat flow in the upper 100 m of the well. The long-term monitoring showed that at Caravelinha soil is by 2–4 K warmer on the annual mean than air without any evident trend of the difference over the observational period of 20 years. It confirms a constant air-soil temperature coupling on the decadal scale that justifies use of the surface air temperatures for simulations of the subsurface temperature field response to the climatic changes. The recent temperature-time changes in the Caravelinha well were simulated using the air temperature series from meteo station Lisbon with a record since 1856 that displays warming trend of 3 K/100 yrs in the last 50 years. The simulated profile agrees fairly well with the observed one.

## AS25-0794

# A new Quality-Controlled Heat Flow Database for Europe

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The Global Heat Flow Database (GHFDB) of the International Heat Flow Commission (IHFC) is under systematic evaluation to ensure its accuracy and usability for the scientific community since 2021. We present a new quality-controlled heat flow dataset for Europe, which contributes to the newly compiled GHFDB. The database is structured according to the global standards on heat-flow metadata scheme and quality evaluation framework developed by the IHFC. By integrating both modern and historical heat-flow measurements, it provides a comprehensive dataset enriched with detailed metadata, essential for geothermal research. The quality assessment follows a systematic approach based on three critical aspects of heat-flow data: methodological quality, numerical uncertainty, and environmental site perturbations. These factors are combined into a single quality score, enabling data comparison and the easy identification of missing or insufficient documentation. The European dataset includes over 22,000 heat-flow measurements collected from 1939 to the present, with varying levels of data quality. The presented dataset is quality-controlled and allows refined definition of datasets used for different scientific applications. We expected it to play a crucial role in geothermal energy exploration and research, serving as a valuable resource for both scientists and industry professionals. This presentation will highlight advancements and challenges of the European heat flow database.

## AS25-0796

# Complexity of geothermal systems in wedge-top basins: Insights from a 3D geological model of the Tertiary Piedmont Basin, NW Italy

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Foreland and wedge-top basins host geothermal systems, in which the nature and architecture of reservoir units, heat sources, and fluid circulation result from a complex tectonic evolution. However, the relationship between tectonics and local geological processes (e.g., sediment dispersal and fracturing), is often not obvious in wedge-top basins, hindering the exploration of their geothermal resources. To investigate the multiscale tectonic-geothermal relationship, we focus our study on the Tertiary Piedmont Basin (TPB), a wedge-top basin formed on the Alps-Apennines junction (northwest Italy). The geometry and thermal structure of the region arise from the interaction between the Alps and Apennines, including processes such as slab break-off, mantle upwelling, and orogenic collapse. The basin fill is up to 6 km-thick and characterized by several unconformity-bounded clastic units, encompassing shelf to deep-water depositional settings. Their spatial arrangement reflect major depocenter shifts and structural regime transitions. The presence of several thermal springs, local high geothermal gradients (>80 °C/Km), and moderately high surface heat flux suggest a deep groundwater circulation, most likely within the highly fractured Alpine basement rocks.

We present a conceptual basin-scale 3D model of the reservoir and overlying sealing sedimentary cover, implemented through the analyses and integration of different geological/geophysical data (e.g., seismic reflection lines, structural and petrophysical data), along with a synthesis of the main tectonic events that affected the basin. This model helps unravel possible heating mechanisms and circulation of the geothermal waters in the TPB and the applied workflow can be used on analogue basins to estimate their geothermal potential.

## AS25-0911

# Geological, geophysical and petrophysical data integration for the geothermal energy potential assessment of the Romagna and Ferrara folds, Eastern Po-plain

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The thermal energy stored within the earth's crust is a renewable source of energy that can be harnessed to help achieve the ambitious commitment of the European Green Deal, which targets a 55 % reduction in $CO_2$ by 2030. Development of this resource, however, requires a proper assessment of the geothermal prospect to reduce the risks associated with drilling unsuccessful, costly geothermal wells. The InGEO (Innovation in GEOthermal resources and reserves potential assessment for the decarbonization of power/thermal sectors, www.ingeo.cnr.it) project seeks to develop an innovative exploration workflow for combining muti-parameter datasets. It focuses on exploring the geothermal potential of the sector of the Northern Apennine buried—structures of the Romagna and Ferrara Folds (RFF), where a thermal anomaly attributable to deep fluid circulation within the deep-seated Mesozoic carbonate sequences was identified. We integrate geophysical, geological and petrophysical data for evaluating the subsurface thermal regime in the RFF region. First, we utilized previous seismic tomography models to develop a consistent 3D seismic model, by applying a clustering algorithm. The seismic models were next inverted to estimate the spatial variation of the thermal regime. Using geological (well logs, seismic lines, stratigraphic columns), petrophysical (thermal and acoustic measurements on rock samples of representative units of the RFF region) and thermal measurements from boreholes as constraints, we perform a thermophysical characterization of the area, to evaluate the RFF's geothermal potential in the next stage.

InGEO is a PRIN 2022 PNRR Project and has received funding from the European Union, Next Generation EU.

## AS25-0918

# Compilation of terrestrial heat flow data and new advances in China

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We have comprehensively compiled China's terrestrial heat flow data—through addition, deletion, correction, and recalculation, the national dataset now comprises 2,337 data points with an average heat flow of 67 mW/m². Nationwide, two high heat flow regions are evident: The Indo-Tibetan collision zone (Southwest China) exhibits a hot crust–cold mantle regime dominated by elevated crustal radiogenic contributions, while Eastern Asia, influenced by the subduction of the Western Pacific plate, displays a hot mantle–cold crust regime with higher mantle heat flow. In terms of new advances, this study focuses on the spatial distribution and genesis of anomalous heat flow as well as its vertical variations. For instance, numerical simulations in Northeast China reveal that the Moho temperature—the initial thermal structure of the lithosphere—is a crucial and sensitive parameter controlling magma migration: low Moho temperatures hinder intrusion, moderate temperatures allow magma to erupt, whereas high temperatures cause magma to accumulate within the crust. This mechanism explains the lack of volcanic activity within the Songliao Basin. Moreover, global scientific drilling indicates that, beyond shallow influences, high radiogenic heat production contributes significantly to vertical heat flow variations in certain regions.

## AS25-0950

# Vertical variations of thermal properties and heat flow in a 550 m deep fully cored borehole in Litoměřice, Czechia

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A 550 m deep fully cored borehole drilled as a part of a large geothermal project in Litoměřice (50°32'04.42"N, 14°09'09.14"E, 173 m a.s.l.), Czechia, in 2024/25 was used for a detailed study of the thermal properties of the encountered Quaternary, Cretaceous and Permo-Carboniferous sedimentary rocks. Thermal conductivity and diffusivity of the drill cores was measured with a depth step of one meter immediately after the drilling, i.e. in a water saturation state close to in situ conditions. Each sample was measured by two techniques—the optical scanning method and the Hot Disc method enabling determination of thermal properties both along the bedding and perpendicular to it. Later on the measurements were repeated on oven-dried samples. The difference between water saturated and dry samples was studied as a function of their porosity and the results were compared with the published data. The obtained profile of the vertical conductivity together with the equilibrium temperature gradient was used for determination of the vertical heat flow density. Its variations with depth were interpreted as a manifestation of both the transient state of the subsurface temperature field caused by climate changes and the convective heat transfer especially in the upper section of the well in the highly porous Quaternary and Cretaceous sedimentary layers.

## AS25-1013

# Geothermal resources for the energy transition of the Yukon Territory (Canada): New heat flow data to improve geothermal potential assessment

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The Yukon Territory, although the smallest of Canada's three territories, has a land surface area of almost 500,000 km$^2$ and is home to 45,148 inhabitants. Despite the majority of the territory being connected to a territorial electricity grid sourced by renewables (hydroelectricity and wind generating over 80% of Yukon's electricity), space heating is mostly provided by diesel. Heating Degree Days below 18 ºC are over 7,500 in the Territory, which highlights the importance of space heating for the people living in the Yukon.

Geothermal energy could be an option to provide baseload heating (and electricity or combined heat and power) to the Yukon homes and decrease the diesel consumption in the territory. For this reason, new temperature-gradient data acquired in the Yukon were analyzed to provide heat flow assessments to improve the Yukon heat flow map.

First, the temperature profiles were corrected for topographic-induced thermal disturbances. Then, surface heat flow was estimated by solving a 1D inversion heat conduction problem through mathematical optimization and considering a theoretical paleoclimate history. The combination of these new heat flow assessments with the previous heat flow map for the Yukon suggest that the southern part of the Territory has greater than average heat flow values (90–126 mW/m$^2$) associated with major fault zones crossing the region, which could be potential targets for deep geothermal exploration in the territory.

## AS25-1142

# Thermal model of La Palma Island from a data-integrative approach

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The Canary Islands stand out as a key region within Spanish territory with considerable potential for harnessing high-enthalpy geothermal resources due to their active volcanic systems. La Palma, one of the youngest islands in the archipelago, has experienced at least seven volcanic eruptions over the past 500 years, the most recent occurring in 2021. Despite these indicators of geothermal potential, the development of high-enthalpy geothermal power plants on the island has not been pursued. This hesitation is primarily due to the financial risks associated with such projects and the lack of detailed geophysical data necessary for accurately characterizing the island's geothermal resources.

To address these challenges, adopting a data-integrative approach to better characterize potential geothermal sites can help reduce uncertainties and support the planning of drilling phases in such projects. Following the 2021 eruption, several new geophysical experiments and studies have been conducted on La Palma to investigate the current subsurface configuration. In this study, we integrate these recent geophysical datasets to develop a three-dimensional hydrothermal model of the island to investigate the underlying heat transfer mechanisms, and to evaluate the influence of the thermal and hydraulic properties of rocks and fluids in governing the spatial distribution of temperature.

## AS25-1215

# Analysis of heat flow and radiogenic heat contribution for geothermal exploration in Mexico

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Heat flow is a relevant parameter in geothermal exploration, and heat generation by radioactive elements is an important contribution to the surface heat flow. Regional exploration in Mexico has been based predominantly on the concurrence of high heat flow and recent volcanic activity. However, it has been observed that in some areas where recent volcanism is not present as a relevant heat source, high heat flow values occur, mostly related to the heat produced by the elevated content of uranium, thorium and potassium in the local crustal rocks. Presently, the heat generation data has been restricted to few locations but its importance in the regional exploration projects has promoted the efforts to collect all information on data about the chemical concentration of U, Th and K. Here, we present the data mining results to assemble a map with the available information of radioactive heat generation and its influence on the reported heat flow values. The results highlight high heat generation values that are distributed in areas overlooked by exploration projects due to the lack of recent volcanic activity, even though they might conceal geothermal resources to support the energy transition in Mexico.

## AS25-1220

# Heat flow determination and lithospheric thermal structure in the southeastern coastal region of China

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The Cathaysia Block, located in the southeastern coastal region of China, is characterized by complex geological history and abundant geothermal resources, providing an excellent site for geothermal research. The terrestrial heat flow measurements and lithospheric thermal structure studies conducted in this region are not only significant for understanding regional geological and geophysical characteristics, but also offer crucial theoretical and technical support for geothermal resource exploration and development. As a key parameter reflecting Earth's internal thermal state, heat flow serves as an essential basis for lithospheric thermal structure analysis, geodynamic studies, and regional geothermal resource potential assessment. In this study, through the addition of new measurement points, heat flow values were calculated, revealing the current thermal state of this region.

## J11 45 Years of Milestones in Lithosphere and Solid Earth Research with ILP

### AS25-0176

# Continental lithosphere – assemblage of microplates with fossil fabrics deciphered by passive seismic experiments

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Formation and evolution of the continental lithosphere, one of the ILP research themes, still belongs to fundamental questions often debated within different geoscience disciplines. Data from passive seismic experiments, realized during last few decades at scales from the small-size local/regional experiments up to the large pan-European ones, enable to unravel in details lithosphere structure. The most recent large-scale experiment, the AlpArray (AA) including its complementary experiments, and currently running experiment AdriaArray (AdA), record data for mapping structures in broader central and south-eastern Europe, respectively. Investigation of seismic anisotropy in three dimensions provides a unique constraint on tectonic fabrics and character of past and present-day deformations of the mantle lithosphere, which forms the biggest volume of continents. Based on data from passive seismic experiments in tectonically different domains of Archean, Proterozoic and Phanerozoic provinces of Europe, we model the mantle lithosphere fabrics with tilted symmetry and delimit the extent of the domains, as well as shapes of their boundaries from characteristics of changes in orientation of large-scale anisotropy. We associate the tilted fabrics with a systematic preferred orientation of olivine, originally formed by mantle convection in the oceanic mantle lithosphere and later "frozen" in continents. Particularly, the S-shape of the Carpathians-Rhodope mountain chain, surrounding the Pannonian Basin in the north and Moesian platform in the south, deserves the special attention for understanding the European-Adriatic plate collision and its effects on the broader Pannonian region to be surveyed in intended project Plate-scale Modelling of Continental Lithosphere.

## AS25-0559

# Thermal and metasomatic signatures of craton reworking by mantle and plate tectonic processes

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Cratons are considered as stable cores of continents that can survive a long-term interaction with mantle and plate tectonic processes. However, geochemical and geophysical observations suggest heterogeneous modification with possible partial destruction of cratonic lithosphere. Cratonic modification may lead to a significant reduction in lithospheric thickness, metasomatism of cratonic lithospheric mantle, and crustal magmatic underplating and eclogitization. These processes are essentially controlled by the lithosphere thermal state, which makes the backbone of the results. The examples of the lithosphere thermal structure and compositional heterogeneity demonstrate various degrees of lithosphere reworking by mantle and plate tectonics processes.

The lithosphere structure records

- the memory of the Iceland plume passage across Greenland (10.1016/j.earscirev.2018.10.015) although it can hardly be identified from seismic observations,
- mantle fertilization and crustal eclogitization in parts of the East European Craton (10.1029/2018JB017025; 10.1016/j.earscirev.2018.11.004; 10.1038/s41467-021-26878-5),
- mantle metasomatism below the cratonic Siberian LIP region (10.1016/j.epsl.2018.09.034),
- lithosphere heterogeneity of the southern Africa cratons (10.1016/j.gr.2016.03.002, 10.1016/j.gr.2016.05.002),
- substantial preservation of lithosphere below the North China craton (10.1029/2020JB020296), although reworked by two Mesozoic subductions,
- heterogeneous pattern in lithosphere thinning below Tibet (10.1029/2022JB026213),
- incipient ocean spreading below the Arabian shield (10.1016/j.earscirev.2022.103955),
- destruction of the lithosphere of West Antarctica by the Mesozoic subduction in the proposed back-arc settings (10.1016/j.earscirev.2020.103106),
- loss of the cratonic signature by large parts of the East Antarctica craton (10.1016/j.earscirev.2022.103954).

Finally, the lithosphere thermal structure predicts principally different fates of the Greenland and Antarctica ice-sheets (10.1016/j.earscirev.2018.10.015; 10.1016/j.earscirev.2022.103954).

## AS25-0563

# Importance of eclogites from cratonisation to the Phanerozoic explosion of onshore life

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Eclogite formation from lower crustal rocks requires high pressure at relatively low temperature in the presence of water. Due to the high temperature regime in the early Earth and the sparse observations of eclogitic rocks at the surface, it is generally expected that such rocks are rare in cratons. Our recent results show that large amounts of eclogitic lower crustal rocks are present below the seismic Moho in the Baltic Shield (Nature Comm., doi: 10.1038/s41467-021-26878-5). These eclogites in various metamorphic grades may even explain the high topography of the Scandes mountain range in northern Fennoscandia (Nature Comm., doi: 10.1038/s41467-025-55865-3). Our findings suggests that the amount of sub-Moho eclogite can be generally underestimated globally!

Eclogites globally occur at Earth's surface in a large number of locations in Phanerozoic orogens. By interpretation of >18,000 km of seismic profiles, we document that a mafic crustal layer is generally preserved in Proterozoic orogens but absent in Phanerozoic orogens (Geology, doi: 10 .1130 /G52647 .1. This fundamental difference indicates a general change in the global subduction style at the onset of the Phanerozoic, which caused massive eclogitization of newly formed lower crust in orogens and subsequent recycling of the eclogitic rocks into the mantle. The resulting, remaining buoyant felsic crust led to the rise of continents above sea level, which enabled onshore life to develop, thus explaining the Neoproterozoic oxidation event and the explosion of life in the Phanerozoic.

## AS25-0579

# Spreading rate controls cooling subsidence of oceanic lithosphere, type of ocean margins and distribution of ocean hotspots

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Ocean spreading is fundamental part of the Wilson cycle. Ocean age-dependent cooling subsidence is traditionally described by models of thermo-chemical buoyancy of oceanic plates with globally constant parameters, that specify a linear correlation between sqrt(age) and bathymetry. A worldwide analysis demonstrates a strong heterogeneity of isostatic cooling subsidence both between and within oceans. Statistically strong correlations ($R^2$=0.80–0.94) between major characteristics of cooling subsidence and spreading rate indicate that ocean evolution is essentially controlled by spreading rate.

- Slower spreading oceans have higher subsidence rate which implies faster gravitational collapse caused by faster cooling of plates with moderate-to-low MOR mantle temperatures. Fast-spreading oceans have the opposite characteristics.
- The ultraslow SW Indian and the fast-spreading Central Pacific Oceans are the end-members in ocean cooling subsidence, with the Atlantic/NW Indian Oceans plotting towards the ultraslow end, and the Pacific/SE Indian Oceans being closer to the fast-spreading end. The Arctic Ocean and the Atlantics north of the Charlie-Gibbs Fracture Zone deviate from the global trends.
- Ridge-push dominates tectonic forces in slower-spreading, narrower oceans with passive margins. Slab-pull at active margins is a dominant tectonic force in faster-spreading oceans with half-width exceeding 4250 km.
- The age of seafloor flattening, controlled by distribution of hotspots on ocean floor, correlates ($R^2$=0.76) with spreading rate, and thus is not fully random.

Recognition that spreading rate controls ocean evolution with formation of active or passive ocean margins dominated by slab-pull or ridge-push contributes to advances in understanding driving forces in geodynamics.

### Reference

Artemieva I.M., EPSL, 2024, https://doi.org/10.1016/j.epsl.2024.119017.

## AS25-0583

# Crustal melting, underplating and eclogitization at continental plateaux

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The cause of uplift of the world's highest continental plateaux in Tibet, the Andes and East Anatolia is enigmatic. A number of tectonomagmatic processes are proposed to cause their uplift, and it is generally believed that the crustal structure is the key to explaining their high topography. Key factors affecting the crustal structure include the metamorphic formation of eclogitic rocks from lower crustal material, underplating and partial melting of the crust.

We show that the formation of overthickened crust in the Lhasa terrane of Tibet may have led to metamorphic formation of large amounts of dense, eclogitic lower crustal rocks immediately after formation with subsequent delamination, leaving behind a purely felsic crust with a thickness of up-to 80 km. This process has contributed significantly to the rise of this part of the Tibetan Plateau (Nature Comm., doi: 10.1038/s41467-021-21420-z).

Based on our new receiver function interpretation of the East Anatolian Plateau and the transition into the Arabian Shield, we demonstrate the presence of an up-to 20 km thick underplated layer and a 10 km thick intra-crustal partially molten layer. The low density of these layers explains isostatically the high topography in eastern Anatolia (Nature Comm., doi: 10.1038/s41467-024-53435-7). The thicker crust in Tibet and the Andes show similar characteristics, and by a comparative study we show that the high topography of all three plateaux can be explained by isostatic uplift due the low density of these layers containing pockets of partially molten rocks.

## AS25-0677

# The Lithosphere of East Antarctica and how it influences the ice sheet, and its outlet glaciers, from beneath

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The East Antarctic lithosphere, and asthenosphere beneath, is the dynamic foundation for ice sheets and other Earth system components. Insights into these structures were gained through the extensive geophysical campaigns of the 2007/08 International Polar Year, and improved coverage of airborne and satellite data. Geological and geochronological syntheses have also contributed to available datasets for Antarctica. Multivariate studies, using statistical and machine learning based inference to make use of multiple lines of evidence, have recently added greatly to the previously available deterministic studies in constraining the form of the lithosphere and spatial variation of properties such as geothermal heat. Hence, we have a basic understanding of how the lithosphere in turn influences the ice sheet, with the ice-bedrock interface zone as a key region of interaction, including heat transfer and water flow.

This contribution reports on new constraints on lithospheric structure, including those from new ground-based campaigns enabled by the Geophysical Research Infrastructure for Antarctica (GRIT) Facility. These deployments include seismic, geoelectric and GNSS results, heralding a new generation of data collection tailored to the machine-learning age. We find that Earth-ice interactions are important boundary conditions for initiatives that aim to improve the prediction of ice sheet response to changes in atmospheric and ocean forcing. Our ongoing challenge is to capture the variability in deep Earth structure, and the diversity of sub-ice processes, at sufficient detail and with sufficient rigour in multivariate and computational approaches to truly represent the interplay between the solid Earth and the systems it supports.

## AS25-0748

# Seismic evidence for delamination-driven mantle upwelling beneath the Hoh-Xil Basin in the northern Tibetan Plateau

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How the Tibetan Plateau grew farther north from the India-Asia collision boundary has profound implications for understanding the mechanics of continental deformation and accretion. Lithospheric delamination and associated mantle upwelling have been inferred beneath the Hoh-Xil Basin in the northern Tibetan Plateau, supported by widespread active magmatism coeval with rapid uplift since the Miocene. However, in-situ seismic constraints have been limited due to the region's inaccessibility. In this study, we combine ambient noise tomography and shear wave splitting analysis to investigate the structures of the crust and upper mantle, using recently available data from linear seismic arrays across the Hoh-Xil Basin. Our three-dimensional *S*-wave velocity model reveals a partially molten crust in the Hoh-Xil Basin, manifested as widespread low-$V_S$ anomalies, which is spatially correlated with strong uppermost mantle low-velocity anomalies and young exposed magmatic rocks. Shear wave splitting measurements across the Hoh-Xil Basin at approximately 89° E reveal significant E-W-oriented splittings reflecting variability in mantle dynamics, as indicated by the estimated anisotropy depth of 150−200 km and the alignment closely with the absolute plate motion of the Tibetan Plateau. The delay times of these splittings peak at ~1.8 s in the northern Qiangtang Terrane and gradually decrease as *SKS* travel-time residuals increase toward the northern margin of the plateau, coinciding with the northward migration of young magmatism. These findings provide compelling evidence for the mantle upwelling beneath the Hoh-Xil Basin driven by extreme lithospheric thinning, suggesting that the plateau grew northward through lithospheric mantle removal and subsequent magmatic accretion.

## AS25-0990

# The Global Geoscience Transects (GGT) Project: a landmark in lithospheric research

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The Global Geoscience Transects (GGT) Project was one of the oldest and perhaps most successful initiatives of the International Lithosphere Program (ILP). Launched in 1985, it marked a milestone in geoscientific research by integrating geological and geophysical data to enhance our understanding of the Earth's crust in different tectonic settings. This collaborative effort, supported by the International Union of Geological Sciences (IUGS) and the International Union of Geodesy and Geophysics (IUGG), enabled systematic global comparisons of lithospheric structures down to the upper mantle. A key feature of the project was the standardized 1:1 million scale, which allowed for direct comparisons of transects worldwide. These strip maps, typically 100 km wide but of variable length, combined surface geology with deep geophysical data, including seismic, gravity, magnetic, geochemical, and borehole information.

In 1991, a second phase began under my leadership Rick Williams (US), and Sabine Schmidt (Germany), introducing digital data formats. From 1995 onwards, all transects were published digitally. It marked the transition from hand-drawn transects to their digital successors. By the program's conclusion in 1998, over 25 additional transects had been produced, including numerous Chinese profiles, reflecting China's strong commitment to the project. The GGT Project was one of ILP's most enduring and impactful initiatives, significantly advancing global lithospheric research. This tribute is also a heartfelt thank you to Dr. Jim Monger, with whom I had the privilege of leading this project for nearly a decade. His expertise and dedication were instrumental to its success.

## AS25-1018

# Geophysical signature of Precambrian mantle suture zones

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One challenge in recognizing Precambrian collisional orogens is the absence of well-defined suture zones. Because the interface between eclogites and peridotites can produce strong reflection, dipping reflections in the uppermost mantle have been widely interpreted as mantle suture zones. The Yangtze Craton in South China is generally regarded as an Archean-Paleoproterozoic continental nucleus with a coherent basement that collided with the Cathaysia Block in the Early Neoproterozoic. Here we reprocessed a 300-km-long NW-trending seismic reflection profile in the eastern Yangtze Craton. High amplitude events reveal the nearly flat Moho at depth of ~40 km and SE-dipping mantle reflections extending from ~54 km to at least 100 km beneath the eastern Sichuan fold-and-thrust belt. We interpret these mantle reflections as a fossil subduction zone within the eastern Yangtze Craton, which was probably linked with a buried Paleoproterozoic orogen beneath the Xuefengshan belt. The fossil subduction zone corresponds to a remarkable boundary of S-wave velocity and electrical conductivity in the upper mantle, confirming different lithospheric mantle properties beneath the eastern Yangtze Craton. Hence the Yangtze Craton should be formed by the collision or accretion of microcontinents prior to the Neoproterozoic. During NW-ward crustal shortening in the Middle Jurassic, this mantle suture zone controlled the thick- to thin-skinned structural transition from east to west due to tectonic inheritance. Compared with seismic observations in the North China Craton, we propose that the boundary of seismic velocity or electrical conductivity cannot be reliable evidence of mantle suture zones, especially in reactivated Precambrian terranes.

## AS25-1022

# The lithospheric heat flow global data assessment project: state of the art and developments

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The Global Heat Flow Database (GHFD), managed by the International Heat Flow Commission (IHFC) operating under the International Association of Seismology and Physics of the Earth's Interior (IASPEI), is the principal repository for global terrestrial heat-flow data. The latest GHFD release from 2024 includes over 90,000 heat-flow data points worldwide and is freely accessible online with links to primary publications. The current format of the GHFD was established only in 2021 and, in 2023, a data quality-assurance framework was integrated to classify heat flow data by uncertainty, measurement method and local physical processes that may affect the reported values. These enhancements allow researchers to filter and use data according to their specific needs. The ongoing data compilation is part of a broader global effort to provide terrestrial heat-flow data through a modern digital infrastructure following FAIR data and OPEN science principles. In synergy with the IHFC mission, Task Force VIII of the International Lithosphere Program (ILP) is coordinating a systematic review and recompilation of the entire GHFD into the new database structure with pre-defined vocabulary for the metadata. This paper presents the state of the art, the ongoing work and the initiatives adopted by the ILP Task Force VIII to achieve the project goals. The expected outcomes will provide accessible, quality-assured terrestrial heat-flow data to constrain lithospheric evolution models and support the interpretation of other potential field geophysical data sets (e.g. gravity and magnetics) for resource exploration programs.

## AS25-1163

# Lithospheric Thermal Structure of Continental China and Its Tectonic Implications

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Studies of heat flow and lithospheric thermal structure not only constrain lithospheric thickness, geophysical properties, and tectonic evolution but also support practical applications in geothermal resource assessment and hydrocarbon exploration. We compiled and updated China's terrestrial heat flow dataset to include 2,337 measurements, with an average value of 67 mW/m². The spatial distribution shows distinct patterns: high values in eastern and southwestern China, moderate values in central regions, and the lowest values in northwestern cratonic areas. In particular, the Indo-Tibetan collision zone exhibits a "hot crust, cold mantle" structure with elevated crustal heat production, while the eastern margin of Asia—impacted by subduction of the western Pacific Plate—displays a "hot mantle, cold crust" regime dominated by mantle heat. Conversely, northwestern cratonic regions show a "cold crust, cold mantle" pattern.

Recent advances from our group have focused on the role of thermal structure in controlling magma intrusion and its tectonic implications. Numerical simulations indicate that the Moho temperature, representing the lithosphere's initial thermal state, is a critical parameter for magma migration: low Moho temperatures inhibit intrusion; moderate temperatures permit magma to erupt; and high temperatures lead to magma accumulation within the crust. This mechanism explains the absence of volcanism in the Songliao Basin compared to active volcanism in its periphery. Moreover, variations in thermo-seismic lithosphere thickness suggest that Northeast China lies in a mantle-active zone, with these variations closely linked to mantle upwelling and downwelling processes.

## AS25-1268

# Considering data-based heterogeneity in models of lithosphere deformation

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A quantitative description of how the present-day architecture of the crust and lithosphere as well as the heterogenous density configuration of the uppermost mantle jointly influence deformation in orogenic systems is still a matter of debate. We use data-derived 3D configurations as input to simulate the 3D density, thermal and rheological configuration of the lithosphere and assess how those relate to observed seismicity. With examples from the Alpine Himalayan System, we show how the thermal and rheological configuration relates to intracontinental seismicity. We find that a critical crustal thickness controls continental deformation up to which strength increases whereas strength decreases for values larger than this critical thickness. Moreover, we test the influence of the upper mantle thermal and density configuration on the present-day dynamics. Considering a detailed crustal model of the Alpine region and its forelands consistent with available geoscientific observables we test an ensemble of configurations of upper mantle thermophysical properties derived from published seismic tomography models. Using a Gibbs-free energy minimization algorithm (https://zenodo.org/records/6538257) we convert the results of regional shear-wave seismic tomography models to temperature models and define the base of the lithosphere and the geometry of slabs in the asthenosphere with a threshold temperature of 1300 °C. We model topography and deformation velocities as resulting from buoyancy-forces driven by a quasi-instantaneous flow resulting from the first-order rheological structure of the lithosphere-asthenosphere system using the simulator LAMEM (https://doi.org/10.5281/zenodo.7071571).

## AS25-1450

# Coupled surface to deep Earth processes: Contributions from TOPO-EUROPE to climate- and energy-related societal challenges

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The TOPO-EUROPE initiative of the International Lithosphere Program (ILP) serves as a pan-European platform for integrated surface and deep Earth sciences, synergizing observational studies of the Earth structure and fluxes on all spatial and temporal scales with modelling of Earth processes. The most notable innovations include (1) a process-based understanding of the connection of upper mantle dynamics and absolute plate motion frames; (2) improved conceptual understanding of the temporal evolution from back-arc extension to tectonic inversion and onset of subduction; (3) concepts governing the interplay between thermal upper mantle processes and stress-induced intraplate deformation; (4) constraints on the record of vertical motions from high-resolution data sets obtained from geo-thermochronology for Europe's topographic evolution; (5) recognition and quantifications of the forcing by erosional and/or glacial-interglacial surface mass transfer on the regional magmatism, with major implications for our understanding of the carbon cycle on geological timescales and the emerging field of biogeodynamics; and (6) the transfer of insights obtained on the coupling of deep Earth and surface processes to the domain of geothermal energy exploration.

We discuss multidisciplinary research and community building across many scientific frontiers, including research on the biosphere, climate and energy. This includes interactions between glaciation, sea level change and deep Earth processes; the sensitivity, tipping points, as well as the role of rock melting and outgassing in affecting such interactions; the emerging field of biogeodynamics; and tightening the connection between societal challenges regarding renewable georesources, climate change, natural geohazards, and novel process-understanding of the Earth system.

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