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S01a - Observational Seismology - Open Session

Status of the ISC Datasets for Seismology

DOI: 10.57757/IUGG23-1117 - LINK

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The mission of the International Seismological Centre (ISC) is to produce the most long-term and complete Bulletin of instrumentally recorded seismicity on a global scale. We describe recent achievements in rebuilding the entire ISC Bulletin using the new ISC locator, ak135 velocity model and more robust magnitudes. We explain the plans of extending the Bulletin with earthquake solutions and station readings in the early instrumental period (1904-1963). We note the recent ISC efforts in constraining the depths of moderate to large seismic events by taking the depth phase arrival time measurements from the waveforms freely available on-line and building Probabilistic Point Source Model solutions (ISC-PPSM). We also explain the future of the International Seismograph Station Registry (IR) and its place within the FDSN registry of seismic networks.

In addition, we produce several specially designed data products that stemmed from the ISC Bulletin and allowed ISC to assist several different areas of seismological research. These datasets include ISC-EHB dataset (1964-2020), ISC-GEM catalogue (1904-2019), IASPEI Reference Event List (GT, 1959-2020), ISC Event Bibliography (1904-2023). We also describe the supplementary datasets: the Electronic Archive of Printed Station/Network bulletins, the Seismological Dataset Repository, and the International Seismological Contacts.

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S01a - Observational Seismology - Open Session

Understanding North Sea seismicity for risk mitigation of large-scale CO2 injections

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Carbon capture and storage technologies are an essential part of EU's decarbonisation efforts. Combined with sustainable energy resources, they are necessary to move Europe towards a net zero carbon emissions economy. Containment risk evaluation includes analysing natural seismicity patterns in the North Sea, where several Mt-scale CO_2 storage projects are being developed. Within the framework of the ACT project SHARP Storage, an extensive unique earthquake bulletin was compiled using seismicity data from all relevant data centres. The bulletin is stored using the IASPEI Seismic Format (ISF). Preliminary processing included duplicate removal and explosion identification. In total, 15,230 events were recorded between years 1382 and 2022, of which 5,408 were identified as likely or potential explosions. For the remaining events, waveforms are currently being collected as a basis for further analysis, including event relocation and magnitude homogenisation.

The magnitude of completeness of this data set varies both spatially and temporally. The most seismically active regions in the study area are the Viking and Central grabens. Coastal areas are populated with more events than the central part of the North Sea due to the denser distribution of seismic stations onshore allowing for the detection of smaller ($M<3$) magnitude events.

Moment tensor inversion, shear-wave splitting measurements, and stress drop analysis will be compared to and complement a review of borehole stress measurements to better gauge the present-day stress field. This is crucial for the understanding of the reservoir and caprock response to large-scale CO_2 injection over time.

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S01a - Observational Seismology - Open Session

The characteristics of seismogenic zone in eastern Taiwan: Implications from seismic b-value

DOI: 10.57757/IUGG23-0534 - LINK

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Taiwan is located on a convergent boundary of the Eurasian Plate and the Philippine Sea Plate. It is one of the countries that have experienced the most earthquakes worldwide. The eastern region of Taiwan is directly above the collision zone and is the most frequent and active with domestic earthquake activity. The areas also have dense dynamic fault systems which located in the Yilan, Hualien, and Taitung areas. Those areas record huge amount of earthquakes yearly. Since seismic b-value has been investigated in different periods throughout Taiwan in the past, they have not yet to study the b-value of the eastern region of Taiwan in detail. Therefore, this study uses the earthquake catalog integrated by the Central Weather Bureau to analyze the spatial-temporal variations of b-values in east Taiwan. The seismic events recorded from January 1996 to June 2019 are adopted. Areas with a low seismic b-value often represent potential areas where major earthquakes are likely to occur. Our results indicate that in eastern Taiwan, the overall b-value has generally demonstrated a decreasing trend in recent years. The rapid re-accumulation of internal stress possibly caused by the compression of the two plates and the ongoing seismogenic behavior. The potential for a catastrophic earthquake is exceptionally high. Therefore, we should act appropriately at any time.

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S01a - Observational Seismology - Open Session

Coexistence of thin-skinned and thick-skinned tectonics near the deformation front in southwestern Taiwan: Implication from a dense seismic array

DOI: 10.57757/IUGG23-0458 - LINK

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While many studies suggested that thick-skinned deformation may occur in the interior of a mountain belt and a thin-skinned contraction wedge is predominant near the foothills, we report the coexistence of both thin- and thick-skinned deformation beneath the foreland basin in southwestern Taiwan based on the high-resolution microearthquake distribution observed by a dense seismic array. We revealed three major tectonic elements in our study area, which are

1. A basal decollement of the thin-skinned wedge at a depth of about 5 km beneath the foothills and coastal plain.
2. A westward-dipping backthrust extending from the foothills to a depth of about 15 km beneath the Coastal Plain.
3. Foreland-vergence blind thrusts rooting on top of the backthrust at depths below ca. 8-15 km.

The foreland-dipping back thrust may result from reactivating an ancient normal fault for being associated with an inverted half-graben. Our numerical modeling further demonstrated that this pre-existing normal fault becomes a passive roof thrust during later orogenic contraction. The rotation and westward movement of this backthrust would compress the rocks in front of it and create blind thrusts beneath the Coastal Plain. This thick-skinned deformation may also have affected the overlying tectonic wedge by building a ramp on the shallow decollement. As a result, the proto-Dajienshan fault might form at the ramp where stress concentrates.

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S01a - Observational Seismology - Open Session

Focal parameters analysis of earthquakes in the S-SE of the Iberian Peninsula (1900-1962)

DOI: 10.57757/IUGG23-0871 - [LINK]

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The objective of this study is to review the Seismic Catalogue of the National Geographic Institute of Spain (IGN, Instituto Geográfico Nacional) for the largest earthquakes occurred in the S-SE zone of the Iberian Peninsula during the period 1900-1962 using all the available information, some of them not used previously. These observations are very heterogeneous, so we have also established a methodology, that allow to evaluate it and thus be able to carry out a joint analysis of the data.

We have selected 16 earthquakes with maximum intensity larger than V and re-evaluated the intensity and the epicenter. Our results shown that at the IGN intensity was overestimated for 9 events with greater variations than one intensity degree in 4 earthquakes (for example from VII to V-VI on November 25th, 1913, earthquake, in Granada). The main factor for these changes in the intensity is the use of the EMS-98 scale that take in the vulnerability of buildings. Only for the April 25th, 1912, earthquake, intensity was underestimated, IV versus the new IV-V intensity.

We have also re-evaluated the epicenters reviewing both macroseismic and instrumental information. We have updated the epicenter of 13 earthquakes with greater variations than 10 km in 4 cases. The largest epicenter modification corresponds to August 11th, 1913 (I_{max}= VII), earthquake. There is a confusion with the name of the population that suffered the greatest effects, and for this shock its macroseismic epicenter has been moved 41 km to the NW from the IGN epicentre using contemporary sources.

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S01b - Observational Seismology - Open Session

Rotational ground motion recordings in the West-Bohemian/Vogtland region: 6-component waveforms for inversion for seismic moment tensors

DOI: 10.57757/IUGG23-1822 - LINK

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The West-Bohemian/Vogtland region (Germany/Czech Republic) is well known for its frequent intraplate swarm activity related to fluid flow within the crust. Previous studies found that non-double-couple components (non-DC: isotropic, CLVD) contribute significantly to the seismic moment tensors of these events. They were interpreted as tensile faulting associated with the migration of deep magmatic fluids through the crust. However, so far the results are restricted to a few larger events. The accurate and precise determination of non-DC components during waveform inversion for moment tensors is difficult, especially for smaller magnitude events (M<3.5).

In earlier synthetic studies the joint inversion of translational and rotational waveforms improved the resolution of the moment tensor. In this project "NonDC-BoVo" – funded within the frame of the ICDP EGER project – two rotational sensors were deployed collocated with translational seismometers. The acquired data present one of the first examples using field data to invert waveforms for the moment tensor. The sensors show a good sensitivity even for low magnitude events. In seven months, the "Seismologie-Verbund zur Erdbebenbeobachtung in Mitteldeutschland" reports 521 events occurring within a distance of up to 30 km.

Here, we present data examples together with an estimation of the magnitude of completeness from rotational recordings. Based on the signal-noise-ratio, we estimate a magnitude of completeness of around 0.3 for the rotational data compared to -0.7 from the catalogue. We found that the transversal translation corresponds well to the vertical rotation for a phase velocity of 2000 m/s at frequencies of 10-20 Hz.

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S01b - Observational Seismology - Open Session

From the laboratory to the field: A traceable on-site calibration approach for seismometers

DOI: 10.57757/IUGG23-3271 - [LINK]

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Braunschaweig, Germany

As part of the EU-funded joint research project "Metrology for low-frequency sound and vibration - 19ENV03 Infra-AUV" laboratory calibration methods for seismometers in the low frequency range down to 0.01 Hz have been developed. These procedures provide the possibility of traceable on-site calibration during operation for field sensors without disturbing the regular measurements and allow an accurate determination of amplitude and phase along with measurement uncertainties. This is of special interest for stations of the Comprehensive Nuclear-Test-Ban Treaty Organization's (CTBTO) International Monitoring System (IMS), which are required to be operational 100% of the time.

The on-site calibration procedure requires a reference sensor co-located to the operational station sensor and the record of sufficient coherent excitation signals within the relevant frequency range. The gain ratio between the station sensor under test and the reference sensor is calculated and subsequently multiplied with the precise frequency response of the reference provided by the newly developed laboratory calibration methods, yielding the frequency response function for both amplitude and phase of the station sensors including site-specific factors.

We present results of on-site calibration tests performed at the seismic IMS station PS19 in Germany using reference seismometers calibrated by laser interferometry in the laboratory. The results deviate less than 5% from the nominal response function for frequencies between 0.01 Hz and 20 Hz for all components. The traceable determination of the response for the individual components in detail improves the sensor and data quality; subsequently waveform amplitudes can be estimated correctly.

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S01b - Observational Seismology - Open Session

Exploration and Application of Gravitational Curvatures Changes in Earthquake Deformation

DOI: 10.57757/IUGG23-1694 - LINK

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The objective of this study is to enhance the observation and understanding of earthquake deformation by developing a method for describing coseismic changes in gravitational curvatures (GC). GC are third-order derivatives of the Earth's gravitational potential, represented as a 3-D tensor matrix with twenty-seven components, ten of which are independent. To achieve this, we first investigate the dislocation Love numbers of the Earth's gravitational potential and derive the Green's functions of GC caused by four independent point sources in a spherical inhomogeneous Earth model. The forms of changes in a half-space Earth model are then presented. Furthermore, a sensitivity study is conducted on three physical quantities involving gravitation, gravitational gradients, and GC to determine their usefulness in seismic source depth detection. Our numerical results show that changes in the GC are more sensitive to the medium information of the field source compared to gravitation and gravitational gradients. This finding indicates that measurements of GC could provide more detailed information on slip fault parameters when considering heterogeneous slip. The method was successfully applied to the 2011 Tohoku-Oki earthquake. In conclusion, measurements of the third-order derivatives of the gravitational potential have great potential in solid Earth studies, especially in light of the launch of the *Gravity* Field and Steady-State Ocean Circulation Explorer (*GOCE*) satellite mission. However, further work is needed in terms of instrument design and development.

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S01b - Observational Seismology - Open Session

How seismometers tilt in response to atmospheric pressure variations: the case of the Hunga Tonga Lamb wave.

DOI: 10.57757/IUGG23-2918 - LINK

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The Hunga-Tonga eruption excited atmospheric Lamb waves that circled the globe multiple times and were recorded by barometers and broad-band seismometers of the Global Seismic Network (GSN). Their dominant period was 45 minutes with typical amplitudes of 2-3 hPa.

Based on our previous work we expect that the response of horizontal seismometers at these periods is dominated by tilts due to two distinct physical mechanisms, LDT and TWT: local tilt due to warping of the seismic vault floor (LDT) in response to atmospheric pressure variations and a regional tilt (TWT) due to a lateral pressure gradient along the surface.

We have inspected all the GSN recordings of the Hunga Tonga Lamb wave and only retained 21 stations with clean baro- and seismograms. We find that for any three component sensor the tilt due to vault deformation points in a fixed, sensor specific direction independent of the propagation direction of the Lamb wave. Furthermore we find that LDT is larger than TWT at 80% of retained GSN stations. While accelerations can be well modelled in most cases, pressure gradient induced ground tilts point towards Hunga Tonga for only 7 stations.

Curently we lack any model which would allow us to explain the observed TWT tilt directions for the remaining 14 stations as we do not think that deformations of the Lamb wave front due to wind or atmospheric temperature variations can account for the observed tilt misalignments.

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S01b - Observational Seismology - Open Session

Simulation of atmospheric waves induced by the 2022 Hunga-Tonga volcanic eruption——New insight into the Lamb waves

DOI: 10.57757/IUGG23-1368 - LINK

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The 15 January 2022 eruption of the Hunga-Tonga volcano generated huge explosions in the atmosphere, which excited various kinds of atmospheric disturbances detected globally by ground-based or spaceborne instruments. Here we show our simulations of these atmospheric waves along with a summary of observation findings. The modelling is achieved by a complete synthetic seismogram calculator (QSSP) considering a hybrid approach of the normal mode theory and matrix method in a layered spherical Earth model including the atmosphere. The synthetic waveform profile, the spectra for nearby stations, as well as the dispersion curves extracted in an array all show good agreement with the observations. Based on these results, especially the dispersion curves for phase speed, we propose a new interpretation for the horizontally propagating Lamb wave. In this model, the Lamb wave can be regarded as the fundamental gravity modes in low frequency band and the fundamental acoustic modes in high frequency band, respectively. The findings may provide new perspectives on the analysis of general atmospheric waves and show the potential of seismic techniques on atmospheric problems.

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S01b - Observational Seismology - Open Session

Seismic-based characterization for Volcano-Induced landslides: a feasibility study based on the 2018 Anak-Krakatau volcano flank collapse

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The 22 December 2018 Anak-Krakatau volcanic flank collapse triggered a devastating tsunami along the Sunda Strait coast, highlighting the need for tsunami early warning systems to detect both volcanic collapse and landslide tsunami triggering from real-time seismic data. Seismically, landslides are deficient in high-frequency radiation compared to tectonic earthquakes. In this study, carried out in the framework of the TSUNAMI_RISK project, we implemented spectral analysis and back-projection to locate low-frequency events (40-70 s) along the Indonesian coast, specifically volcano-induced landslides. Using the Indonesian seismic network, we successfully detected and located the Anak-Krakatau volcanic flank collapse. The back-projection method allowed us to estimate the location about 100 seconds after the event initiation, with detection achieved with stations up to 1° from the source. To assess potential biases in our approach, we evaluated two weeks of continuous long-period seismic data (11-25 November 2019) from high-risk volcano tsunami areas in eastern Indonesia, such as Batu Tara, Iliwerung, Gamalama, and Sangeang Api. We conclude by discussing the expected false alarm rates for various warning thresholds based on the current network configuration in Indonesia and explore the routes to implementing this approach for operational tsunami early warning.

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S01c - Observational Seismology - Open Session

UPFLOW OBS body wave tomography of the whole mantle column beneath the Azores/Madeira region

DOI: 10.57757/IUGG23-3396 - LINK

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We present preliminary tomographic results obtained within the ERC-funded UPFLOW (Upward mantle flow from novel seismic observations; https://upflow-eu.github.io/) project, which led a passive seismology large-scale experiment in the Azores-Madeira-Canaries region starting in July 2021 and ending in September 2022.
We recovered 49 (out of 50) ocean bottom seismometers (OBSs) deployed in a ~1,000×2,000 km2 area and with an average station spacing of ~150-200 km. We present an initial set of ~6000 multi-frequency (T ~2.7-30 s) body-wave travel time cross-correlation measurements generated with the UPFLOW OBS data from more than 150 teleseismic events. We show a glimpse of the preliminary P-wave tomographic model built with this new dataset. We then combine UPFLOW's OBS data with global seismic data from temporary and permanent stations to obtain an expanded set of ~600,000 measurements. This dataset is used to construct a global P-wave model with enhanced resolution in the entire mantle column beneath the Azores/Madeira/Canaries region. We compare our new, high-resolution model with existing global tomography models and discuss its geodynamical implications.

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S01c - Observational Seismology - Open Session

The seismicity of the Madeira archipelago – hints for active volcanism and/or tectonic faults?

DOI: 10.57757/IUGG23-3348 - LINK

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[3]*Instituto Dom Luiz IDL- Universidade de Lisboa- Instituto Superior de Engenharia de Lisboa, Geosciences, Lisbon, Portugal*

Madeira is discussed to be a hotspot volcanic complex in the Northeast Atlantic placed on 140 Ma old oceanic lithosphere. Catalog seismicity beneath and around Madeira is sparse and hypocenters are often not well constrained due to lack of station coverage. In 2020 and 2022 two events with Mw 5.3 and Mw 4.9 were widely felt on the island. We used data of a local seismic network consisting of 24 temporary stations in the years 2011-2012 and up to 4 permanent stations to reveal the local seismicity in the Madeira archipelago. We used an adapted velocity model and the LASSIE detection software and found more than 220 additional events, which we located using HYPOSAT. Most of the events concentrate about 30-40 km south of the main island with hypocenter depths in the range of 20 up to 40 km. The seismicity stops at the south coast of Madeira and starts again north of the main island. Other zones of activity are found in the East of Madeira and in the vicinity of Desertas Grande island southeast of Madeira. Hypocenter depths beneath Madeira cluster between 10 and 20 km depth at Moho or sub-Moho level. Our data support the hypothesis that the center of volcanic activity in the archipelago might nowadays be associated with the southern end of the Funchal Ridge.

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S01c - Observational Seismology - Open Session

Shredded subducted Nazca plate leaves slab-fingers behind, in the mantle Beneath southern Costa Rica

DOI: 10.57757/IUGG23-1242 - LINK

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Subduction of parallel transform faults, at an oblique angle, generates jumps in age of the subducted oceanic lithosphere and produces pronounced bending of the subducting oceanic slab-fingers. Cocos plate subducts/collides under the Panama block in southern Costa Rica. A sequence of north-south parallel transform faults, the Panama Fracture Zone (PFZ), shreds and obliquely subducts fingers of Nazca Plate under southern Costa Rica and southwestern Panama, along an east-west margin. The oblique convergence of these slab-fingers causes the subducted fingers, once quasi anchored in the mantle, to stay behind as the PFZ moves westward with respect to the mantle, producing bending of the slab-fingers as the Cocos plate subducts above them.

For decades, the lack of a dense seismic network in southern Costa Rica has inhibited the acquisition of a detailed geometry of the subducting plates in this region. For that reason, intermediate depth earthquakes (Z 50-80 km) recorded under southern Costa Rica and straight projected to the trench, were interpreted as steep subduction of the young and buoyant Cocos plate. Alternatively, they were interpreted as intra-plate events along the deepest portion of an almost flat subducting Cocos plate.

Based on precise earthquake locations recorded with a dense broadband seismic network in southern Costa Rica, constructed and installed to capture seismic activity associated with the next Osa large (Mw 7.2-7.4) earthquake, we propose here a new model, according to which, seismic events deeper than 50 km occur on subducted fingers of Nazca plate stuck in the mantle, under southern Costa Rica.

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S01c - Observational Seismology - Open Session

Seismotectonics of Hornsund, Spitsbergen, European Arctic, based on moderate magnitude seismicity

DOI: 10.57757/IUGG23-2782 - LINK

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Accurate seismotectonic studies on and around Spitsbergen, European Arctic, are impeded by a number of difficulties. The largely glaciated environment and the geographic distribution of land and sea restrict geotectonic mapping, as well as the deployment of dense, local seismic networks. The nature of tectonic seismicity in the region, which is episodic and dominated by moderate to low event magnitudes, imposes additionally its own challenges. So far, the best studied activity has been the Storfjorden 2008-2016 earthquake series (Mw 6.1, 21 February 2008; Mw 5.1, 29 March 2016) and background seismicity in the offshore area east of southern Spitsbergen, and to a lesser extent, seismicity in Heerland, on central Spitsbergen (mb 5.5, 18 January 1976). Despite the aforementioned challenges, the improvement of the regional seismic network from 2010 onward, has been offering enhanced insight into Svalbard seismotectonics, in particular in areas best covered by seismic station distribution. One such case, is the Hornsund area, where the calculation of moment tensor solutions was possible for two moderate magnitude, onshore events (Mw 4.3, 4 July 2015; Mw 4.6, 31 May 2017). The nearby broadband station facilitates event focal depth determination, insights into the local tectonic structure enabled by geological mapping. We will present the focal characteristics of the activity associated with these earthquakes and discuss their placement within the local and regional geotectonic setting.

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S01c - Observational Seismology - Open Session

Microseismicity associated with the Hebron Fault in SW Namibia – a case study of earthquake clusters in stable continental regions

DOI: 10.57757/IUGG23-0857 - LINK

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[1]*University of Cape Town, Department of Geological Sciences, Cape Town, South Africa*
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[3]*Department of Geology, University of the Free State, Bloemfontein, South Africa*

The Hebron Fault lies within southwestern Namibia, a stable continental region. It features a prominent northwest-trending scarp which displaces Quaternary alluvial fans and channels. The scarp has a length of 45 km, a maximum height of 10.1 m and an average height of 5.9 m. Fault scaling relationships suggest the scarp formed in 2–5 events of Mw ~7. Interestingly, geomorphological analyses only found evidence for a single event. In common with other major paleoseismic fault scarps in southern Africa, no earthquake cluster is recorded near the Hebron Fault in regional catalogues.
In order to investigate the possibility of missed low-magnitude seismicity, below the detection threshold of the regional networks, a network of 23 4.5 Hz three component geophones was installed around the Hebron fault scarp. Earthquakes were identified using a STA/LTA coincidence trigger and P and S wave arrivals were manually picked. More than 200 earthquakes were located near the Hebron Fault with Ml ≤ 3.6 to a maximum depth of 20 km. A regression through the hypocentres results in a plane corresponding to the expected fault plane. Observed earthquakes at the Hebron Fault may either represent a long-lived aftershock sequence or a form of background seismicity associated with the fault.
The fact that the earthquake cluster associated with the Hebron Fault was missed by regional networks suggests that seismic hazard can be overlooked, particularly in stable continental regions where seismic networks are often not well developed and the repeat-times of large earthquakes are longer than the instrumental record.

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S01d - Observational Seismology - Open Session

Lithospheric structure beneath the ultra-slow spreading Knipovich ridge using noise reduced OBS P-wave Receiver functions

DOI: 10.57757/IUGG23-1638 - [LINK]

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Ultra-slow spreading ridges are characterized by huge volcanic complexes which are separated by up to 150 km long amagmatic segments. The mechanisms controlling these types of mid-oceanic ridges (MOR) are not yet fully understood. We aim to constrain the crustal and mantle structure beneath a segment of the Knipovich ridge (Greenland Sea) by using Receiver functions calculated from teleseismic events.

Seismic data, recorded on the ocean bottom, are highly contaminated by different noise sources. Results of our noise reduction algorithm based on harmonic-percussive separation (HPS) techniques of selected KNIPAS station data show a significantly reduced noise level on all three seismometer components (below 1 Hz).

Improving the SNR on OBS records reveals the superposition of water and sediment reverberations on the crustal structure information, the latter is strongly hindering the structure interpretation. Here, we compare the real data with a set of synthetic Receiver functions for better analysis of the lithospheric structure. The results of the real data stacks reveal two discontinuities beneath the ridge shoulders: (i) at depths of around 8 km, which can be most likely associated with a Moho, (ii) at depths of around 30 km, which can be linked with the lithosphere- asthenosphere boundary. The center of the MOR and the Logachev seamount are characterized by a strong low-velocity zone at depths of up to 20 km. Comparing the depths of the mantle transition zone discontinuities from KNIPAS data and land station data indicates a low velocity layer east of the Knipovich ridge in the uppermost mantle.

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S01d - Observational Seismology - Open Session

Unraveling the western portion of Parecis Basin by Receiver Function

DOI: 10.57757/IUGG23-3578 - LINK

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The Parecis basin is located in the Midwest region of the Brazilian territory, with approximately 6000 meters of accumulated sediments. We used receiver function data from 5 temporary broadband stations belonging to the Parecis Basin Tectonic Studies network supported by CNPq and a permanent station from the Brazilian seismographic network, all located in the Parecis Basin. Then the HK stacking method and Common stacking point (CCP) of the Receiver Function data were applied, The application of the HK method allowed us to determine a Vp/Vs that varies from 1.74 to 1.89 along the profile and a crustal thickness that varies from 25 to 43 km. In the CCP profile, it was possible to observe the Moho and determine the probable basement of the basin. In addition, an intermediate region between the Moho and the basement was noticed, which was interpreted as the Conrad discontinuity. Therefore, in general, the applied methods showed results consistent with previous studies carried out in the Basin and it was noted that the CCP stacking promoted an evolution in the interpretative aspect of the structures.

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S01d - Observational Seismology - Open Session

Reykjanes Peninsula (SW Iceland) seismicity in the last 10 years

DOI: 10.57757/IUGG23-1724 - LINK

Jana Doubravova[1], Rognvaldur Magnússon[2], Diana Konrádová[1], Josef Horálek[1],
Tomáš Fischer[3], Thorbjorg Ágústsdóttir[2], Egill Gudnasson[2]
[1]Institute of Geophysics- Czech Academy of Sciences, Seismology, Prague, Czech Republic
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[3]Charles University, Faculty of Science, Prague, Czech Republic

Reykjanes Peninsula (SW Iceland) is extraodrinary place from the geophysical perspective. Lying on the on-shore part of the Mid-Atlantic Ridge, interlaced by volcanic systems and hosting sevral high temperature geothermal areas the seismic activity on Reykjanes Peninsula is generally persistent often on a microseismic level but occasionally reaching up to ML~5-6. Throughout the years many temporary seismic stations or small to medium size local seismic networks have beed deployed there for various purposes from geothermal prospection monitoring to short time passive seismic experiments. We analyzed 10 years period of recording of the natural seismicity recorded at the stations of the semi-permanent local seismic network REYKJANET (in operation since 2013) together with several permanent stations of SIL network present in the area of interest. This timespan contained times of relative rest, several small earthquake swamrs associated with purely tectonic origin as well as very turbulent and active periods with magnitudes up to ML=5.4 related to volcanic eruptions. We study the distribution of foci of the background seismicity as well as for the several seismically active periods with consistent set of stations.

We compare different automatically derived earthquake catalogs and their common features like the aseismic zones or upper and lower limit of the foci occurence, seismogenic faults and void areas. The dataset contains also Fagradalsfjall volcanic system dyke intrusions related events in 2021-2022.

We deal with several tens of thousands of foci with high quality stable location imaging the subsurface beneath Reykjanes Peninsula.

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S02a - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

The Marsquake Service: Seismic monitoring on another planet

DOI: 10.57757/IUGG23-3732 - LINK

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[1]ETH Zurich, Swiss Seismological Service, Zurich, Switzerland
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[4]IPGP, Earth Science, Paris, France
[5]Imperial College, Earth Science, London, United Kingdom

For more than four years the Marsquake Service (MQS) detected and catalogued marsquakes from near realtime data recorded by SEIS, InSight's seismometer deployed on the surface of Mars. Now that the data collection phase of the mission is over, we review the procedures and methods developed by MQS and describe the contents of the catalogue. With only a single station, there are obvious challenges in providing a catalogue for the entire planet. Due to the low SNR of marsquakes and the extreme variability of background noise, impulsive seismic signals are rarely evident and standard automated algorithms cannot be used to identify marsquakes, and manual review was needed.

The MQS tools are based on best practice and standards used in seismic networks on Earth, for example we use a single station interactive analysis GUI based on SeisComP. Consistent procedures were developed to distinguish marsquakes from atmospheric noise or other data anomalies, classify events, pick phases, determine distance using a suite of Martian velocity models which has been updated during the mission, determine back azimuth, and locate events. Mars magnitudes are assigned using calibrated magnitude relations.. The final catalogue includes over 1300 marsquakes. Six events are known meteoroid impacts confirmed from visual imaging, their proximity to MQS locations confirms our location methodology. The catalogue contains quakes from within 1 degree of the lander out to 146 degrees distance and magnitudes span from 1 to 4.6. Body waves, crustal phases, surface waves, atmospheric shock waves and even core phases have been observed.

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S02a - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

A new seafloor cable-type observation network in the western half of the anticipated Nankai Trough earthquake source area: N-net

DOI: 10.57757/IUGG23-1127 - LINK

Shin Aoi[1]*, Tetsuya Takeda*[1]*, Takashi Kunugi*[1]*, Masanao Shinohara*[1,2]*, Takayuki Miyoshi*[1]*, Kenji Uehira*[1]*, Masashi Mochizuki*[1]*, Narumi Takahashi*[1]
[1]*National Research Institute for Earth Science and Disaster Resilience, Network Center for Earthquake- Tsunami and Volcano, Tsukuba, Japan*
[2]*Earthquake Research Institute the University of Tokyo, Center for Geophysical Observation and Instrumentation, Tokyo, Japan*

The area off the Pacific Ocean in eastern Japan has already been densely monitored by S-net, and in western Japan by DONET and the JMA's Tokai and Tonankai cables. However, the area from off Kochi to the Hyuga-nada, which is the western half of the anticipated Nankai Trough earthquake source area, is a blank area of observation. To eliminate the blank, NIED is now constructing Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net). N-net consists of two subsystems, one inshore and one offshore, connecting two landing stations. Each subsystem has 18 observatories connected by a fiber-optic cable approximately 700 to 800 km long, for a total of 36 observatories. N-net is designed as a hybrid system based on the inline system, but with the plug-in node system that allows for future addition of observation equipment. Each observatory is equipped with two pressure gauges for tsunami observation and two accelerometers and short-period velocity meters for earthquake observation to ensure redundancy. For installation on the N-net, NIED has developed a pressure gauge that is less susceptible to pressure measurement due to seismic shaking and attitude fluctuation, a pressure-resistant enclosure that transmits pressure accurately, and an implementation of IP packets on SDH payloads. The observed data will be transmitted to JMA in real time and used for early warning of earthquakes and tsunamis. Offshore system will be laid till 2024, and the construction will be expected to be finished till the spring of 2025.

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S02a - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Smart Sensor Deployments in the Tokyo Area: New Means of Communicating Earthquake Risk and Chances for Seismology

DOI: 10.57757/IUGG23-3372 - LINK

Naoshi Hirata[1], Danijel Schorlemmer[2], Hiroshi Tsuruoka[1], Takashi Furuya[3], Hiromichi Nagao[1]
[1]University of Tokyo, Earthquake Research Institute, Tokyo, Japan
[2]GFZ Potsdam, Seismic hazard and risk dynamics, Potsdam, Germany
[3]Institute of Scientific Approaches for Fire & Disaster, Research and Development Department, Tokyo, Japan

Affordable devices based on MEMS acceleration sensors have seen a rise in recent years. We have explored the utility of the smartphone-type sensors built into small devices directly plugged to power outlets in the wall for the use by volunteers and companies. We deployed 10 devices to private people in the Zama region, southwest of Tokyo, in 2021 and 50 devices in the larger Tokyo region in 2022 for about a half year each. Additionally, we have equipped the 48-story Tokyo Metropolitan government building in Shinjuku, Tokyo, with many devices on floors ranging from 1st to 44th, and one 6-story building of the Tokyo Narita International Airport with many devices on four floors. All devices have provided us with both three-component acceleration records and seismic intensities in the Japan Meteorological Agency (JMA) scale, which is familiar to non-professional Japanese people. The measured seismic intensities on different floors and within the same floor show a variety of values different to the reported JMA intensity for the wider area. Also, we have obtained human assessments of experienced seismic intensity. Basically, the felt and measured intensities are consistent with some significant outliers. Our original hypothesis is that people with sensors at home are more sensitive and better prepared and behave more reasonably when experiencing large-intensity shaking. We were not able to clearly prove it yet due to a lack of a strong-shaking event during the experiment. We are planning to expand the experiment to more than 1000 households in the Tokyo area.

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S02a - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Truaa Earthquake Early Warning System for Israel –Operational Stage and the Public's Perspective

DOI: 10.57757/IUGG23-1433 - [LINK]

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Truaa - Israel's Earthquake Early Warning System (EEWS), is in operational mode since January 27th, 2022. Israel is amongst the few countries in the world to run a national, government- operated EEWS. Building and operating such a system involves not only many technical challenges, but also considering the social aspects of alert strategy and public's perceptions.

In the determination of an alert magnitude threshold, there is an inherent tradeoff between urgency and necessity. In this presentation we combine three independent data sets to inspect Israel's alerting strategy: (1) We analyze the performance of the EEWS in the past two years to derive uncertainties of earthquake early warning alerts in Israel; (2) We re-project these uncertainties to the historic earthquake catalog of 2010-2020 and (3) We analyze a dataset of unnecessary injuries following missile alerts, to estimate the potential toll of unnecessary earthquake alerts.

We then present the social point of view of alerts in Israel, as obtained by a first-of-its-kind questionnaire in Israel, focusing on people's perceptions and perspective on earthquake alerts.

Taken together, we find that the expected injury toll from unnecessary alerts is an order of magnitude lower than the potential damage of shorter reaction time (the time period between the alert and s-wave arrival) and that the public's preferences may allow the alerting strategy to be less conservative, and to accommodate the EEWS uncertainties and limitation by allowing potentially faster alerts.

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S02a - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Active rifting in the East African rift and challenges in disaster risk management: Efforts made by ESARSWG member countries

DOI: 10.57757/IUGG23-0480 - LINK

Atalay Ayele[1], *Fred Tugume*[2], *Annie Milwozi*[3], *Anesu Chibi*[4], *Iguano Helio*[5], *Ghebrebrhan Ogubazgh*[6], *Gladys Kianji*[7], *Patrick Rafiki Rafiki*[8], *Michael Msabi*[9]
[1]*Addis Ababa University, Institute of Geophysics Spacve Science and Astronomy, Addis Ababa, Ethiopia*
[2]*Geological Survey of Uganda, Geophysics, Entebbe, Uganda*
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[9]*University of Dodoma, Geophysics, Dodoma, Tanzania- United Republic of*

The roughly 3000 km long East Africa Rift system (EARS) is one of the striking features of the African continent that captures all stages of rift development from the most juvenile to nascent seafloor spreading in Okavango delta and Afar depression, respectively. It provides a natural laboratory for studying a fundamental, and yet enigmatic, component of plate tectonics. A mechanism for rupturing thick, cold, continental lithosphere is not readily apparent in conventional models of mechanical stretching. However, magma production weakens the plate and serve to localize strain, thus better facilitating rifting. Studies of seismicity and volcanism provide insights into this problem and a variety of geophysical, geochemical and geological studies can be used to better understand the role of the crust and mantle in continental breakup.

Permanent seismic station distribution is sparse in the continent but some focused and detailed studies have been conducted using temporary broad seismic networks in collaboration with overseas researchers. Earthquakes of magnitude $M > 7.0$ are observed in EARS from instrumentally recorded seismicity (the 1910 Rukwa earthquake in Tanzania, the 1990 earthquake in South Sudan and the 2006 Machase earthquake in Mozambique) which is a wakeup call for the fast growing construction industry in the region. It is also inferred that the EARS is more active than we think, from recently recorded seismicity, which requires collaborative efforts to enhance studies in the region both for basic science research and disaster risk management purposes.

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S02a - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

The African Seismological Commission (AfSC): Recent activities and perspectives

DOI: 10.57757/IUGG23-1014 - LINK

Paulina Amponsah[1], *Mohamed Elgabry*[2], *Mimoun Chourak*[3], *Grobbelaar Michelle*[4], *Gladys Kianji*[5], *Mustapha Meghraoui*[6]
[1]*School of Nuclear and Allied Sciences- Ghana Atomic Energy Commission, Nuclear Earth Science, Legon-Accra, Ghana*
[2]*National Research Institute of Astronomy and Geophysics, Egyptian National Data Center, Cairo, Egypt*
[3]*EcoleNationale des Sciences Appliquees-oujda-University Mohamed Premier, Mechanics and Applied Mathematics, Oujda, Morocco*
[4]*Land use and infrastructure Unit, Council for Geoscience, Pretoria, South Africa*
[5]*University of Nairobi, Department of Earth and Climate Science, Nairobi, Kenya*
[6]*Institut des Physique du Globe de Strasbourg, Ecole and observatoire des Sciences de la Terra, Strasbourg, France*

The African Seismological Commission (AfSC) is a scientific organization established in 2014 by the International Association of Seismology and Physics of the Earth's Interior (IASPEI). It is one of the four regional Commissions of IASPEI. The official launching of the African Seismological Commission was in January, 2014 at the University of Witwatersrand, Johannesburg, South Africa. The mission of the Commission is to promote the science of Seismology within the scientific community of Africa, by promoting research studies, enhance scientific cooperation and train young scientists. In October, 2022 for the first time, a joint General Assembly was held for the African and Asian Seismological Commissions. The joint General Assembly was hosted by the National Research Institute of Astronomy and Geophysics, and was held close to the natural boundary between Asia and Africa in the Hurghada, Red Sea, Egypt. The event was conducted in hybrid (both in-person and online) mode, with more than 180 participants, 140 participated physically and 40 online, from 38 Countries. Since the AfSC launch meeting in Johannesburg in 2014 and subsequent 3 General Assemblies (2016 Aswan, 2018 Al Hoceima, and 2022 Hurghada), diverse resolutions have been undertaken such as increasing the number of AfSC country members, promoting the organization of a Seismological Centre for Africa as well as having an earthquake emergency response team in place in Africa. In addition, the General Assemblies hosts training session for students and young researchers in all topics in seismology, seismotectonics, earth structures, and seismic hazards and risks.

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S02b - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Outcomes Following a 2022 International Workshop on Global Earthquake Monitoring

DOI: 10.57757/IUGG23-4342 - LINK

William Yeck[1], Paul Earle[1], Harley Benz[1], Michelle Guy[1], John Patton[1]
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In 2018, the U.S. Geological Survey (USGS) hosted an international workshop titled "Future Opportunities in Regional and Global Seismic Network Monitoring and Science", in which members identified and prioritized areas of research to improve global seismic monitoring. This meeting directly informed the USGS National Earthquake Information Center's (NEIC) 5-year strategic plan. The international, real-time, sharing of parametric earthquake data was identified as a critical area of development that could improve monitoring. The need for rapid parametric data sharing became even more apparent following the COVID-19 pandemic, as many monitoring operations were strained. As all monitoring agencies have similar missions, to rapidly report on earthquakes and their effects in efforts to mitigate impacts, the community can greatly benefit by mutually supporting each other through automatic information sharing.

In 2022, the NEIC hosted a follow-up workshop supported by the USGS Powell Center. The workshop prioritized updates following the COVID-19 pandemic and addressed the specific task of international parametric data sharing. We discussed how to rapidly communicate operational information between our agencies (e.g., system outages), the types of automatic derived earthquake data we should be sharing, and infrastructure requirements. The working group decided to explore automatically sharing picks and moment tensors, leveraging easily deployable messaging software such as Apache Kafka. We identified other areas where further discussion could benefit our agencies, such as our standard operating procedures (SOPs) for source characterization. Here we will share the outcome of these meetings and discuss how they fit into NEIC's strategic plan priorities.

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S02b - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

EIDA Italian node: seismic data curation preservation e dissemination

DOI: 10.57757/IUGG23-3367 - LINK

Alfonso Mandiello[1]*, Massimo Fares*[1]*, Danecek Peter*[1]*, Stefano Pintore*[1]*, Della Bina Emiliano*[1]*, Diego Franceschi*[1]*, Carluccio Ivano*[1]*, Maniscalco Michele*[1]
[1]*Istituto Nazionale di Geofisica e Vulcanologia, Geofisica, Roma, Italy*

The seismology data archive at Istituto Nazionale di Geofisica e Vulcanologia (INGV), a node of the EIDA federation, currently holds more than 100 TB of seismological waveform data. To guarantee a robust qualitatively superior service needs full care of every step about curation preservation and dissemination of data.

It starts from seismic network inventory management and requires keeping track of all station and network related information and metadata.

Our system has a modular design, whenever possible, by leveraging existing open-source solutions as a customized Tuleap implementation to realize the ticketing system, for injecting and tracking the changes and managing the station's faults. The station metadata and channel responses are managed using the XML database eXist-db to store StationXML documents natively and a new implementation of the fdsnws-station based on it. Then GUI leverages Grafana creating a dashboard to present an overview of the system status of all components.

Then we have deployed an semiautomatic sanity check of data to apply our policies and quality assessment before archive data using a rule manager

Our policy for preservation is to make a replication (synchronized copy) at a new storage archive in Naples and a backup in the tape library.

After all these steps we are ready to disseminate data through webservices and websites (https://eida.ingv.it/).

To complete the service for users we are adding significant computational resources and an adequate processing and analysis framework combining Apache Spark, and ObsPy, creating a "computational archive" where storage resources and computational resources converge.

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S02b - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

The EarthScope Geophysical Cloud Data Platform

DOI: 10.57757/IUGG23-3114 - LINK

Chad Trabant[1], Henry Berglund[1], David Mencin[1], Jerry Carter[1], Rob Casey[1], Charlie Sievers[1], Gillian Sharer[1]
[1]EarthScope Consortium, Data Services, Washington, USA

EarthScope Data Services, a merger of UNAVCO and IRIS data activities, has been supporting the international seismological and geodetic research communities for many decades. Historically, the seismological and geodetic facilities independently managed data repositories on self-managed systems. As a component of merger activities, we have established a project to design, develop and implement a common, cloud-based platform. Goals of this Common Cloud Platform (CCP) project include operational improvements such as cost-effectiveness, robustness, on-demand scalability, significant growth potential and increased adaptability for new data types.

The migration and combination of the data facilities to a cloud computing environment represents a major evolution that will benefit researchers, data contributors, and EarthScope data managers. Researchers and other data users will benefit from the increased capacity, flexibility, new services, and adjacency to nearly unlimited compute. We will be developing training materials and conducting workshops to help data users to take full advantage of the platform, in particular the option of processing data in the cloud which avoids slow transfer across the internet. The new platform will also support hazard assessment and mitigation through continued open data access policies, and in particular by operating the geodetic data collection and initial product generation for the US ShakeAlert system.

The project is currently in a development stage, and we anticipate having a demonstration platform partially operational in mid-2023 and fully operational by the end of the year. We will report on the status of the project, as well as anticipated directions and challenges identified so far.

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S02b - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

A broader look at licensing and copyright issues for global seismological data and products from a data center perspective

DOI: 10.57757/IUGG23-2595 - LINK

Florian Haslinger[1], Robert Casey[2], Jonathan Hanson[3], Javier Quinteros[4], Lesley Wyborn[5], Jens Klump[6], Suzan van der Lee[7], Elisabetta D'Anastasio[3], Helle Pedersen[8], Jerry Carter[2], Carlo Cauzzi[1,9], Rémy Bossu[10,11], Fabrice Cotton[12,13]
[1]ETH Zurich, Swiss Seismological Service, Zurich, Switzerland
[2]EarthScope Consortium, Data Services, Seattle, USA
[3]GNS Science, Data Science and Geohazard Monitoring, Wellington, New Zealand
[4]GFZ Potsdam, Geofon, Potsdam, Germany
[5]AuScope, n/a, Canberra, Australia
[6]CSIRO, Mineral Resources, Perth, Australia
[7]Northwhestern University, Earth and Planetary Sciences, Evanston, USA
[8]Université Grenoble Alpes, ISTerre, Grenoble, France
[9]ORFEUS, n/a, De Bilt, Netherlands
[10]EMSC, n/a, Arpajon, France
[11]CEA, n/a, Arpajon, France
[12]EFEHR, n/a, Potsdam, Germany
[13]GFZ Potsdam, Seismic Hazard and Risk Dynamics, Potsdam, Germany

Sharing data - arrival time readings, earthquake parameters, waveforms and further derived products - has for many decades been key to the scientific advancement of seismology and our understanding of the Earth. The establishment of data centers, from institutional to global, that receive, archive, curate and make accessible large volumes of seismological data, following community standards and best practices, was a logical consequence. IASPEI, with its commissions, evolved as a de-facto standards body for seismological data, governed by the community of data providers and users alike.

However, conditions of use for these shared data did not receive much attention by data providers, distributors, and groups working on the definition of standards of data and services. If mentioned at all, generic statements on allowed use were provided somewhere on websites that offered access, often declaring ‘only for scientific/academic purposes’ or ‘not for commercial purposes’. Driven by the desire or requirement to improve FAIRness of our data, better understand data usage and adapt to technological changes, and support open science, putting proper licenses on data and metadata has now become a significant topic.

In this presentation we look at current practices and evolving ideas regarding application of licenses to the holdings of seismological data centers, covering waveforms, earthquake parameters, and further derived products, also including views from other geoscience domains. The relation to (legal) copyright and intellectual property issues, local/national licensing regulations that may hinder a globally uniform approach, and downstream implications for citation, attribution and general re-use of data will also be addressed.

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S02c - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

GEOSCOPE: 40 years of global broadband seismic data

DOI: 10.57757/IUGG23-4675 - LINK

Martin Vallée[1], Dimitri Zigone[2], Nicolas Leroy[3], Jean-Yves Thoré[4], Céleste Broucke[3], Armelle Bernard[4], Constanza Pardo[5], Eléonore Stutzmann[1], Frédérick Pesqueira[6], Maxime Bes de Berc[2], Alessia Maggi[2], Luis Rivera[2], Michel Le Cocq[1], Olivier Sirol[3]
[1]Université Paris Cité- Institut de Physique du Globe de Paris, Seismology, Paris, France
[2]EOST- Université de Strasbourg, Seismology, Strasbourg, France
[3]Université Paris Cité- Institut de Physique du Globe de Paris, Geoscope, Paris, France
[4]EOST- Université de Strasbourg, Geoscope, Strasbourg, France
[5]Université Paris Cité- Institut de Physique du Globe de Paris, Data Center, Paris, France
[6]Université Paris Cité- Institut de Physique du Globe de Paris, Ovpf, Paris, France

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 33 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).

Over the years GEOSCOPE contributed to define today's global seismology standards through the FDSN (data format, data quality level, instrumentation requirements), being the French contribution to the international effort (with GSN, GEOFON and others) towards global seismic observations. The stations are equipped with the best quality seismometers (from the very first STS1 in the early 80's to the last STS-6A and 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, most of the stations are also equipped with accelerometers, pressure and temperature sensors allowing for a wider range of observable events such as the recent Hunga-Tonga eruption. All the data are sent in real-time to IPGP, IRIS-DMC, RESIF, and tsunami warning data centers.

In 2022, a workshop has been organized to celebrate the 40th anniversary of GEOSCOPE and illustrate the main scientific achievements made possible by all the global networks. After a look at the history of the network, the recent evolutions of the observatory in terms of instrumentation and data products (near-real time earthquake analyses) will be presented.

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S02c - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Thirty years of GEOFON

DOI: 10.57757/IUGG23-4631 - LINK

Angelo Strollo[1], Susanne Hemmleb[1], Laura Hillmann[1], Peter Evans[1], Thomas Zieke[1], Javier Quinteros[1], Andres Heinloo[1], Joachim Saul[1], Winfried Hanka[1], Karl-Heinz Jäckel[1], Rainer Kind[1], Frederik Tilmann[1]
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2023 marks thirty years since the start of GEOFON operations with the first three stations in Papua New Guinea (Port Moresby, PMG), the Czech Republic (Moravsky Beroun, MORC), in Ireland (Dublin, DSB). The GEOFON program started shortly after creation of the GFZ German Research Centre for the Geosciences in 1992 with the aim to promote global seismic monitoring, standardisation and data exchange. The program has evolved over the three decades in synergy with the seismological community through three important milestones: since late 1990s the development and community adoption of the SeedLink protocol enabling global real-time data exchange; in early 2000s, development of the Arclink protocol as key development to interconnect the EIDA federated data archives, only recently superseded by the use of FDSN web services at global scale; 2008 as the first public release of SeisComP, one of the most widely used seismological packages in seismology, a development triggered after the 2004 Aceh-Andaman earthquake and tsunami within the GITEWS project (German Indian Ocean Tsunami Early Warning System). Although GEOFON's heritage goes back to the 1990s and further down to 1889 building on the initial findings from Ernst von Rebeur-Paschwitz, the program is capable of leveraging third party funded challenging projects to keep modernising with the community. In this presentation we outline the most important developments of GEOFON through a journey in time over three decades, building links between current activities and vision still influenced by the initial aims which have shaped the current GEOFON mission.

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S02c - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Assessment of seismic-network capabilities in the Netherlands

DOI: 10.57757/IUGG23-4564 - LINK

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Most of the Netherlands is covered with a thick blanket of unconsolidated sediments. In the more consolidated part of the upper crust, different activities are taking place. Oil and gas fields are produced, salt is extracted through solution mining, there is underground storage of liquids and geothermal heat is exploited. All these activities can alter the stress field around existing faults and therewith potentially induce seismicity.

Over the years, an extensive seismic network has been built to monitor seismic activity. To find out whether this network suffices to monitor current and future subsurface operations, the network capabilities have been assessed. To that end, new tools have been developed to compute magnitude-of-completeness and location uncertainty maps over the Netherlands.

The maps show large spatial variation in network capabilities. The main underlying factor is the large variation of sensor density. Another important factor is sensor placement. On average, noise levels are a factor of 25 lower for 200-deep sensors than for sensors at the Earth's surface, in the frequency band that is used for detection (5 to 40 Hz). Moreover, the local setting is important. A regional network in an urban area performs worse than a similar network in a rural area. The tools also provide a means to study design options for future extensions of the network. A scenario layout can be checked for its capability in terms of the minimum magnitude of locatable earthquakes and their associated uncertainty in location.

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S02c - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Update on the Canadian National Seismograph Network

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Natural Resources Canada (NRCan) completed the refurbishment of the Canadian National Seismograph Network in 2019 and has since started commissioning an Earthquake Early Warning System, due to be completed in 2024. We give an overview of these projects and summarize the status of the networks.

Meanwhile, the software, databases and procedures used for location and alerting of earthquakes in Canada are being modernized. NRCan is deprecating AutoDRM and Antelope in favour of an FDSNWS and SeisComP respectively. Custom legacy database schema, file formats, and automatic location and prompt earthquake notification software are being replaced with QuakeLink, StationXML, QuakeML and a commercial software called GDS. The new system will consist of two fully redundant datacentres, with configurations continuously regression tested to ensure continuous improvement. Earthquake solutions from neighbouring agencies will be available to analysts in real time. Some of the SeisComP plugins developed for NRCAN will be of use to other network operators, including new location and magnitude estimators as well as tools for the efficient generation of waveform data availability statistics. Adoption of QuakeML has forced us to develop a clear event type hierarchy and interpret evaluation status meaningfully. NRCan will mark the transition to SeisComP by adopting a new agency code. We report the progress and discuss lessons learned from this process.

Finally, we report on the development of a new system to monitor volcanoes using InSAR, as well as coda envelope moment magnitudes and a regional seismic travel time model for Canada.

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S02c - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

United Arab Emirates national seismic network

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The National Center of Meteorology (NCM) established the United Arab Emirates (UAE) National Seismic Network in August 2008. The network has gone through different evolution phases until it reached its current stage of 23 stations. The main aim of these stages is to enhance the coverage of the network to decrease the gap of observation. A site characterization study at each site included geotechnical and geophysical analyses and microtremor testing. Each station equipped with broadband seismometer, and accelerometer. Since 2017, we started to use the modem with 4G as a communication method instead of the VSAT. Data Acquisition, processing, and interactive analysis is running with SeisComP seismological software package.

Also, the NCM exchanges seismic data in real time with regional seismic networks and receive data from GSN network through internet communication, for better monitoring and understanding of the tectonic setting in the region. Since its establishment, the National Seismic Network provided better view for the seismicity in and around the UAE, and updated the database of local earthquakes catalog.

Additionally, the NCM has a major role in studies related to seismicity and tectonics in the region. It participated in academic studies with national and foreign universities, developing the national seismic hazard and risk maps, and re-examining the building codes incorporation with Abu Dhabi city municipality. The NCM is the prime source of information to crisis management authorities in case of any seismic events and works as a national tsunami warning center and it takes part in public awareness for disaster risk reduction.

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S02c - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Near field tsunami hazard and real-time earthquake monitoring: Challenges for Northern Algeria (Western Mediterranean)

DOI: 10.57757/IUGG23-0010 - LINK

Lübna Amir[1]
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Historical documents and contemporary recorded events show that tsunami hazard exist for northern Algeria (1365: Algiers; 1790: Oran; 1856, Jijel: 2003, Boumerdes). Marked by a coastline of more than 1200 km in length, the country is exposed to a severe risk for earthquake damage. Not only magnitudes up to 7.5 can be reached even if not that frequent but the fast urban growth raises an issue for crisis management in case of a tsunami could be generated meanwhile the people will have to face the ground shaking with vulnerable infrastructures and dwellings. Operational since 2012, France has created its own tsunami warning system for the Western Mediterranean and the Eastern Atlantic, the CENALT. The source is mostly to come from the Algerian coasts.

Today, open-source softwares like seiscomp (developed and maintained at Gempa, Potsdam, Germany) can provide us with good results for automatic solutions of earthquake analysis (magnitude, location). It is nevertheless challenging to estimate the right depth within 15-20 minutes. Earthquake’s analysis is strongly constrained by the number of available phases recorded in real time. Hence, access to open data is crucial for an accurate earthquake parameters estimation. Tsunami warning systems are established at first with automatic solutions.

In this work, we present several cases studies showing how the seedlink protocol for many public networks listed in the FDSN database helps to provide information for tsunami warning bulletins spread to stakeholders and the public audience. These examples serve to expose the challenge faced by the northern Algerian coasts.

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S02d - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

A decade of Indonesia seismicity and its seismotectonic implications: Evaluations from BMKG nationwide earthquake monitoring (2010-2022)

DOI: 10.57757/IUGG23-3804 - LINK

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[3]Agency for Meteorology- Climatology- and Geophysics of the Republic of Indonesia BMKG, Geophysics, Sorong, Indonesia

Indonesia is a seismically active region with a complex tectonic setting. To monitor earthquakes in the Indonesia region, the Indonesian Agency BMKG (Badan Meteorologi, Klimatologi, dan Geofisika) has been operating a nationwide monitoring system using the permanent digital seismometer network of Indonesia (network code IA). However, the earthquake catalog/bulletin resulting from this nationwide monitoring has not yet been evaluated and discussed. In this study, we assessed a decade of seismic activity in Indonesia with a focus on earthquakes from 2010 to 2020 (11 years) and 2021-2022 (two years after significant improvement of the network). We analyzed their parameters, mainly the magnitudes, and compared them with their various magnitude types and moment magnitude by the Global Centroid-Moment-Tensor (GCMT) catalog. A unified earthquake catalog with homogeneous (local) magnitudes is obtained. We evaluated 77,987 earthquakes during this period with the data complete at the local magnitude of 3.5 based on the analysis of their frequency-magnitude distribution (FMD). We then computed seismicity rates of M>3.5 for different regions and tectonic regimes in Indonesia. We also discuss the seismicity 2021-2022 after the significant increase of seismic stations in the IA network. Finally, we discussed seismicity evolution and its seismotectonic implications. Our study is necessary for further seismic hazard assessment in Indonesia.

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S02d - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Aotearoa-New Zealand, geonet national seismograph network: Supporting landslide, tsunami, earthquake and Volcano monitoring since 2001

DOI: 10.57757/IUGG23-0317 - LINK

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Aotearoa-New Zealand islands sit in the South-West Pacific region where tectonic activity generates one of the world largest seismicity, intense deformation, and volcanic activity. Since 2001, GNS Science Te Pū Ao ensures some of the New-Zealand capability to identify, study, prepare and respond to multiple and frequent geological hazard with the GeoNet programme. GeoNet builds and operates a permanent seismological network routinely maintained and upgraded to provide continuous observations for national and regional events, strong motion and building monitoring. Sensors are distributed over the country with regards to population and hazards exposures. GeoNet strives to optimize its network capability and improve its multi-purposes nature. Around 500 near-real time seismic sensors are acquired, archived, and processed into different products over timelines that match a variety of users and requirements. A range of both rapid and curated products are made available for public awareness, scientists and for earthquakes, landslides, tsunami, and volcanic panels and duty officers. We present the current New-Zealand seismological network, flow process and observation settings as it is, today, a mature observation system. We describe a range of derived seismic products and services designed to enable rapid, dynamic, robust, and resilient scientific seismic information to diverse communities with an open data approach from field instrumentation to data archiving. We discuss expectations and incoming challenges to handle technical and scientific transformations with a care for continuous integration process and maintenance required to evolving monitoring, response, and seismology scopes along with modern 24/7 operations center infrastructure strict design and functions.

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S02d - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Using reported parametric data from the ISC Bulletin to evaluate changes in station performance

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Tracking changes in station performance over extended time periods is time-consuming and challenging for many seismic networks. It can also be difficult to compare variations in station performance from different users or station performance between networks. The International Seismological Centre (ISC) receives phase picks for a significant number of networks globally, including from multiple agencies for the same stations. This reported data can be evaluated to provide many metrics for station performance, including average monthly travel time residuals and evaluation of travel time residuals by distance & hypocentre location. We will show how best to access this information which is currently available on the ISC website and outline forthcoming extensions of this functionality. Future features include; a comparison of reported polarities with available earthquake mechanism solutions, providing an indicator for inverted station polarities, response file checks currently being developed by the ISC and station performance metrics for individual agencies. Additionally the station performance metrics are currently undergoing an expansion from only International Registry (IR) stations, managed by the ISC, to including all FDSN stations with picks reported to the ISC. We will summarise the challenges of this expansion and outline how the IR and FDSN station lists will continue to coexist in the future.

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The challenge of a rapidly changing regional seismic monitoring network: the Pacific Northwest Seismic Network, USA

DOI: 10.57757/IUGG23-4768 - LINK

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The Pacific Northwest Seismic Network monitors seismicity in the U.S. states of Oregon and Washington as part of the U.S. Advanced National Seismic System (ANSS). The network has been in existence for more than fifty years and was initially focused on the Puget Sound region in western Washington and several of the Cascades volcanoes. It now covers all of Washington and most of Oregon. Over the decades, the instrumentation and processing software has changed significantly. For example, we mostly operated analog vertical-component short-period stations in the 1970s, 80s and 90s. We first added digital three-component broadband stations in the mid to late 1990s, and since 2000, continuously streaming three-component strong-motion stations. In the past five years, as a partner in the USGS ShakeAlert Earthquake Early Warning system, we have added hundreds of new strong-motion and/or broadband stations. All our data, waveforms as well as derived products, are publicly available. However, users of both our seismicity catalog and old waveform data need to understand that they come with caveats. Here we present several of these caveats including a study of the spatial and temporal variation of the magnitude of completeness of the PNSN catalog.

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S02d - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

The University of Utah Seismograph Stations a Regional Earthquake Center

DOI: 10.57757/IUGG23-2968 - LINK

Kristine Pankow[1], Keith Koper[1], Ben Baker[1], Katherine Whidden[1], Andy Trow[1], Jon Rusho[1], J. Mark Hale[1], Relu Burlacu[1], Jamie Farrell[1], Emily Morton[1], Paul Roberson[1], Josh Alexander[1], Nick Forbes[1], Corey Hatch[1], William Blycker[1]
[1]University of Utah, Seismograph Stations, Salt Lake City, USA

The University of Utah Seismograph Stations (UUSS), a member of the U. S. Advanced National Seismic System (ANSS), operates a regional earthquake center responsible for monitoring seismic events (natural and induced) in both the Utah Region and Yellowstone National Park and for seismic monitoring at the Utah Frontier Observatory for Enhanced Geothermal Energy (FORGE). Additionally, we work with partners in adjacent regions and the U. S. Geological Survey to monitor and study earthquakes throughout the U.S. Intermountain West. UUSS operates a regional and urban seismic network consisting of 250 stations and six infrasound arrays. Here, we highlight a recent assessment of the Utah seismic network capabilities and plans for upgrading legacy analog stations, ongoing work to integrate machine learning and measurement of $M_{w,coda}$ for small (M > 2) regional earthquakes into operations, and the development of an infrasound event catalog. We also highlight observations of some recent earthquakes, including the 2020 M_w 5.7 Magna earthquake.

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The Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG) Seismic Network, Switzerland

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The Bedretto Underground Laboratory for Geoenergies and Geosciences (BULGG) is a unique research infrastructure located in the middle of a 5.2 kilometers long tunnel that connects Ticino with the Furka railway tunnel, in south-central Switzerland. BULGG is equipped with state of the art instruments that allow to conduct experimental research in various fields. From a seismological point of view, we aim to monitor seismicity that occurs during experiments, as well as monitoring local earthquakes, and possibly induced or run-away seismic events. To accomplish that we set up two real-time monitoring systems based on the SeisComP software, i.e. (i) background seismicity monitoring, and (ii) experimental monitoring. The background monitoring, which is the backbone network, consists of surface and tunnel broadband stations, short period sensors, accelerometers, and geophones sampled at various frequencies (200-2000Hz). Acoustic emission sensors, and an accelerometer sampled at 200kHZ constitute the experimental instance. All sensors stream to a common seedlink server which provides data to multiple clients for processing, real-time visualization, archiving, and risk control via dedicated software. A standard workflow is applied to both background and experimental monitoring that includes, automatic picking, automatic phase association and location, and magnitude estimation. Advanced methods are also applied in real-time, such as, real time double-difference relocation, and real-time earthquake detection based on waveform cross-correlation (template matching). Overall, BULGG is a unique environment to test several types of instruments and implement novel methods on observational and network seismology across scales.

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S02e - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

SeisComP - a perspective on its evolution and applications

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SeisComP is nowadays the most widely distributed software package for seismological real-time data acquisition, processing and analysis. Initially developed by GFZ German Research Centre for Geosciences, focusing on data acquisition and exchange as well as basic automatic earthquake monitoring, it has since been enhanced with interactive analysis and fast magnitude calculation for tsunamigenic earthquake warning. Over the years, the SeisComP ecosystem has been extended with open and closed source modules that support additional application domains such as local and induced seismic monitoring, moment tensor inversions, earthquake early warning, seismic and infrasound array processing, structural health monitoring, earthquake engineering analysis, earthquake information dissemination as well as tsunami simulation and decision support. The wide use of SeisComP in over 500 earthquake and tsunami warning services, research institutes, universities and industrial enterprises all over the world has simplified and unified the exchange of seismic data, station meta data and earthquake parameters. SeisComP adopted and formed global standards such as SeedLink, MSeed, QuakeML, FDSN stationXML and FDSN web services. The functionality of the SeisComP ecosystem is growing and under active development and maintenance. We give a perspective on the evolution of SeisComP- past, present and future.

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S02e - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Deep-learning-based phase picking in SeisComP using SeisBench

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The open-source, seismological software package SeisComP is widely used for seismic monitoring world-wide. Its automatic phase picking module consists of an STA/LTA-based P-wave detector augmented by an AIC onset picker. With proper configuration, it allows detection and accurate onset picking for a wide range of seismic signals. However, it cannot match the performance of experienced analysts. Especially broadband data are often challenging for phase pickers due to the enormous variety of the signals of interest.

In order to optimize quality and number of automatic picks and reduce time-consuming manual revision, we chose to develop a machine-learning repicker module for SeisComP based on the SeisBench framework. SeisBench supports several deep-learning pickers and comes pre-trained for different benchmark datasets, one of which was contributed by GFZ Potsdam.

The repicking module consists of several submodules that interact with both SeisComP and SeisBench via their Python interfaces. The current workflow is based on existing locations generated with a classical SeisComP setup. Shortly after event detection and preliminary location, our repicker (1) starts to repick previously picked onsets and (2) attempts to generate additional picks.

Preliminary results are encouraging. The deep-learning repicker substantially improves pick quality over a large frequency range. The number of picks available per event has approximately doubled and the publication delay is often reduced, especially for small events. The total number of published events has increased by about 20 per cent.

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S02e - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

SEISAN earthquake analysis software – background, capabilities, recent developments and future challenges

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The SEISAN Earthquake Analysis Software is used widely at regional, national and local seismic networks and by students and researchers in the field of seismology. SEISAN is applied in the monitoring of all kinds of seismic events: Earthquakes, volcanoes, induced and cryo-generated events. SEISAN provides many different programs, from the basic processing and analysis of seismic events at seismological observatories to more advanced research. Based on a flat file database structure it operates on all platforms. SEISAN has undergone steady development since its launch more than 30 years ago. The design and development of SEISAN is and has been conducted in close contact with end users, to ensure fast and efficient workflows. SEISAN includes a comprehensive manual, a tutorial, training exercises and a mailing list where users and experts share information and help each other. SEISAN workshops have been held regularly since the nineties and have in the recent years been supplemented with online web sessions. To the CTBTO national data centres, SEISAN applications are presented at the forum web site. The recent improvements to SEISAN include QuakeML routines for data exchange, near real time event detection and processing and full channel identification and logging of event processing.

References:

Havskov, J., Voss, P.H. and Ottemoller, L. (2020). Seismological Observatory Software: 30 Yr of SEISAN. Seismological Research Letters, 91 (3): 1846-1852. DOI: https://doi.org/10.1785/0220190313

Ottemöller, L., Voss, P.H. and Havskov J. (2021). SEISAN Earthquake Analysis Software for Windows, Solaris, Linux and Macosx, Version 12.0. 607 pp. University of Bergen. ISBN 978-82-8088-501-2, http://seisan.info

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S02e - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

A continuous evolution: operational seismic monitoring improved capabilities and system modernization coexisting with legacy systems

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The U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) has coupled improving the speed of its 24/7 response with the need to update its system to adapt to continuously evolving technologies. The NEIC is implementing a new analyst interface and corresponding workflow, called “Quick-Look”, for analysts to do a cursory evaluation of rapid automatic seismic solutions to determine to release automatic data to responders, agencies, scientific communities, and the general public. The Quick-Look capability creates the opportunity to distribute validated automatic seismic solutions considerably faster than solutions currently released via the NEIC human-reviewed workflow and policy. We describe this new interface, which utilizes web services and web displays, quantify data release speed increases, and describe the integration with the legacy monitoring and analysis system.

With a small team the NEIC must balance maintaining the existing operational, global, seismic detection, and monitoring software system, addressing issues across data, infrastructure, security, and workflow, while concurrently designing and building a new system with updated infrastructure, technologies, algorithms, and approaches. We describe how the team manages this leveraging shared technologies and approaches across USGS public and internal applications, which includes containers, continuous integration continuous deployment (CI/CD) pipelines, data messaging and web services, and web-based user interfaces. Using a containerized environment coupled with data messaging and web services, the architecture can exploit standardized approaches across multiple applications to support more rapid, secure, and automated deployments, in hybrid and/or cloud friendly, essentially location agnostic, environments.

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S02e - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Magnitude reassessment for digital records of the Belgian seismic network since 1985

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In the frame of the BELSHAKE project, we collected all digital records by the Belgian seismic network of earthquakes with M_L>2 in a dedicated waveform archive and the associated metadata in a database. We visually inspected all waveforms, calculated missing P- and S-arrival times from the Belgian velocity model, and defined noise, P-, S- and coda-windows. We also developed the tools to recompute local magnitudes and to compute new moment magnitudes. One of the main problems we encountered was missing instrument response information for older records. We tried to reconstruct this information based on information in our station database and/or the original data headers. Analysis of station M_L residuals and PSDs of the noise window allowed to select the correct response or to identify unreliable cases.

The definition of the Belgian M_L scale is based on the Lg wave on the vertical component high-pass filtered at 1 Hz. It has been applied systematically since 1985, but unfortunately not all amplitude measurements are preserved in the database. Furthermore, the scale has not been calibrated for distances < 10 km and does not take into account hypocentral depth. These issues are problematic to determine M_L of recent shallow geothermally induced seismicity. We will use our dataset to derive a better formulation of the Belgian M_L scale. We also compute M_W based on spectral fitting of P- and S-waves with the well-known sourcespec package. This will eliminate the need for empirical magnitude scale conversions to compute magnitude-frequency relations for seismic hazard assessment.

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S03a - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Separating Rayleigh and Love waves based on the SPAC method

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The spatial autocorrelation (SPAC) method was developed by Aki (1957) to estimate subsurface velocity structure from the coherence of ambient seismic noise. The SPAC method has been widely used and extended to various cases. Separation of Rayleigh and Love waves is essential to obtain reliable phase velocity dispersion curves. Three-component displacement data is necessary (e.g., Okada and Matsushima, 1989; Chouet et al., 1998). Cross-correlation between the vertical-radial components helps isolate Rayleigh waves (Haney et al., 2012). Recently, the formulation of the SPAC method was extended to strain, rotation, and tilts by Nakahara et al. (2021) and to the mixed correlations between displacement and strain by Nakahara and Haney (2022). Here, we revisit the separation of Rayleigh and Love waves based on these recent developments of the SPAC theory. Isolation of Rayleigh waves is possible using the following components: vertical displacement, areal strain, and tilts. On the other hand, isolation of Love waves is possible using only the vertical-component rotation. Both Rayleigh and Love waves contribute to most auto- and cross-correlation pairs. Therefore, a reasonable method is to isolate Rayleigh waves first and then estimate the contribution of Love waves. Recently, measurements of strain and rotation are becoming possible thanks to the developments of distributed acoustic sensing (DAS) and rotational seismometers. These technical developments, along with the extended SPAC theory, will clearly distinguish Rayleigh and Love waves from ambient noise, which makes it possible to measure radial anisotropy by virtue of the difference between SV and SH velocities.

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S03a - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Inferring micro-crack damage evolution with increasing stress using direct and coda wave velocity measurements in faulted and intact granite samples

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A better understanding of damage accumulation before dynamic failure events in geological material is essential to improve seismic hazard assessment. Previous laboratory tests revealed that such failure events are preceded by a phase of extending micro-cracks, leading to detectable changes in bulk seismic properties. We use seismic velocity estimates to measure changes in micro-crack populations and damage in intact actively and faulted Westerly granite samples. We use an array of 16 piezo-ceramic transducers to send and record ultrasonic pulses and to determine temporal seismic velocity changes. The coda-wave interferometry (CWI) and direct phase arrivals determine velocity changes.

The tests show that: 1) Higher confining pressures increase seismic velocities due to reduced pore space and no hysteresis effects during the unloading cycle. 2) During increasing differential stress, the crack growth before the onset of AE activity is aseismic and could be associated with a monitoring or deformation mechanism. However, the velocity measurement records the changes in a medium way before we observe AE or non-linearity in stress and strain data. 3) Direct waves exhibit strong anisotropy, increasing differential stress and accumulating damage before rock fracture. On the other hand, CWI produces velocity variations that are similar to P-wave velocity changes along the vertical axis. 4) Seismic interferometric measurements are thought to be highly sensitive to changes in the medium. However, we found that such measurements also depend on the type of rock damage (i.e., orientation and shape).

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S03a - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Stratification of heterogeneity in the lithosphere of Mars from envelope modeling of very high-frequency seismic events

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Following its deployment at the surface of Mars, the seismometer SEIS of the InSIght – NASA Mission has detected tens of very high-frequency (VF) seismic events (> 1 Hz). In this work, we constrain the regional attenuation properties of the Martian lithosphere using both impacts and VF data to characterize the heterogeneities and volatile content as a function of depth. To carry out this task, we model the high-frequency energy envelopes of the seismic events using a multiple-scattering approach, considering a stratification of velocity and attenuation in the medium. In a first approximation, we consider a simple attenuation structure composed of a heterogenous crust overlying a weakly inhomogeneous mantle. Our inversion results show that a strongly diffusive and globally dry layer of about 20 km thickness in the vicinity of the InSight landing site (northern plains) suffices to retrieve the shape of near impacts, but the thickness has to be increased to at least 60 km to recover the shape of distant VF events. The observed correlation between the depth extent of the diffusive layer and the thickness of the crust indicates that the main cause of scattering is the lithological heterogeneity. Furthermore, our model suggests that the sources of a number of distant VF seismic events are shallow and located in the southern highlands or in close vicinity of the Martian dichotomy.

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Fine-scale Characterisation of an Active Gas Chimney within the Quaternary Sediments of the Central North-Sea; using Acoustic Full Waveform Inversion

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Integrity of overburden formations to the underlying reservoir rocks plays a vital role in permanent storage of CO_2 within geological traps. Focused fluid escape structures (also known as chimney and pipe structures) are highly permeable (sub-)vertical geological features within the sedimentary rocks that can represent a substantial risk to geological CO_2 storage projects. Despite the importance of such structures to the subsurface hydraulic system, their internal structures and fluid flow properties are poorly constrained to date. In this study, we examined the internal structure of a representative gas chimney underlying the Scanner Pockmark Complex in the North Sea, where methane is currently leaking to the seabed. We recovered an acoustic velocity model of the chimney structure and the host formations, using 3-D full waveform inversion (FWI) technique. The inverted data consists of ~125000 seismic traces from 23 ocean bottom seismometers (OBS) covering an area of 66 km^2. We set the FWI scheme to include only diving waves at offsets of 1300-4600 m, corresponding to incident angles of about 60º to 80º respectively at the maximum well-resolved depth of 700 mbsl. The inverted model, at the maximum frequency of 7 Hz, revealed a complex fluid escape structure with an indirect vertical gas migration pathway that manifested itself as a simple gas pipe structure on a coinciding seismic reflection image. In addition, integration of the recovered velocity structures with a calibrated Gassmann model suggested a patchy gas saturation within the area.

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Seismic attenuation and lithosphere rheology in the eastern margin of the Tibetan Plateau

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Connecting the plateau with cratons in east China, the eastern margin of the Tibetan Plateau is an area with the youngest uplift, strongest deformation, and frequent occurrence of large earthquakes. This region where the topographic characteristics change significantly from south to north becomes an ideal experimental site for investigating the continental geodynamics and seismogenic environment. Most seismological researchers use seismic velocity to constrain the rheological strength and crustal flow distribution in the lithosphere, upon which the deformation can be explored for the crust and upper mantle. However, seismic velocity is related to both rock strength and composition. Therefore, the multiplicity of geodynamic interpretation is unavoidable. However, seismic attenuation is a direct observation of deep temperature and rheological strength. Therefore, we construct a broadband high-resolution layered attenuation model for the lithosphere in the eastern margin of the Tibetan Plateau by using the Pg, Lg, Pn, and Sn waves propagating in the crust and uppermost mantle. The attenuation model provides a fine structure with 3D rheological strength and thermal distribution in the lithosphere. We investigate the dynamic origins of the distribution of soft ductile materials and upon which we exploit the tectonic evolution and seismogenic environment under the lithospheric compression and collision in the eastern margin of the Tibetan Plateau. This research was supported by the National Natural Science Foundation of China (U2139206, 41974061, and 41974054).

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S03a - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Towards a reference attenuation map of Metropolitan France from seismogram envelope modeling

DOI: 10.57757/IUGG23-2032 - LINK

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At high frequency (f>0.5Hz), spatial variations of seismic attenuation parameters -scattering and absorption- control to a large extent the variability of observed ground motions at the regional scale. Hence, our ability to predict seismic hazard depends critically on mapping frequency-dependent attenuation. To address this issue, we developed a hybrid inversion method to separate attenuation parameters (scattering and intrinsic absorption) in 6 frequency bands covering the 0.75 – 24 Hz range from the modeling of the S-wave energy envelopes. Synthetic envelopes and their partial derivatives with respect to attenuation parameters are calculated using the Monte-Carlo method for elastic waves in a simple but realistic model of the Earth's lithosphere. The hybrid inversion method combines a grid-search with an iterative optimization using the Levenberg-Marquardt algorithm, which respectively test different models of random heterogeneities and constrain the level of scattering and absorption.

The inversion procedure has been applied to more than 10000 waveforms retrieved from the database of the French seismological and geodetic network RESIF. The obtained attenuation maps show the extreme variability of frequency-dependent attenuation parameters (scattering and intrinsic absorption) at the regional scale. In particular, we find zones of strong scattering in the Western Pyrenees at all frequencies and in young sedimentary basins below 3 Hz. Absorption is stronger in the Paris Basin at low frequency and in the French Alps above 3-6 Hz. Western France is characterized by weak scattering and absorption. We also find that scattering generally dominates absorption below 1-2 Hz while the opposite is true at higher frequency.

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S03b - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Scattering and absorption imaging of a seismic gap, the Mt. Pollino area (Italy)

DOI: 10.57757/IUGG23-2902 - LINK

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[1]*Università degli Studi di Salerno, Department of Physics, Fisciano, Italy*
[2]*Istituto Nazionale di Geofisica e Vulcanologia, Roma 1, Rome, Italy*
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The Mt.Pollino area is the largest seismic gap in Italy, with faults capable of M6.5-7 but no historical and instrumental M6 events recorded. Between 2010 and 2014 this area has been affected by a seismic sequence of more than 10,000 small magnitude earthquakes and two moderate main events occurred late in the sequence (ML 4.3 and ML 5.0).

The goal of this work is to provide 3D scattering and absorption images of this area using the peak delay time and the coda-Q methods, respectively. Scattering anomalies suggest that the area involved in the sequence is highly fractured, with the strongest scattering contrast interpreted as the Pollino Fault. This large structure acted as a barrier, bounding migration of the seismicity southward, as suggested in recent structural geological works. Declustered high-absorption anomalies mark the area affected by the sequence, suggesting that fluids have played a key role in its development. This result is in good agreement with high VP/VS and high pore pressure anomalies highlighted by recent works on the area.

This work was supported by the PRIN-2017 MATISSE project (no. 20177EPPN2), funded by the Italian Ministry of Education and Research.

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S03b - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Estimation of the depth and frequency-dependent seismic attenuation using acoustic radiative transfer theory

DOI: 10.57757/IUGG23-4428 - LINK

Marcel van Laaten[1], *Ulrich Wegler*[1]
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The acoustic radiative transfer theory is utilized to analyze the propagation of seismic energy in a heterogeneous and random medium, and can be modeled by Monte Carlo simulations. By repeating the simulations and adjusting the non-isotropic scattering and absorption coefficients, the layer-specific intrinsic and scattering attenuation can be determined. The Monte Carlo simulation considers ray tracing in a deterministic and acoustic 1-D model. To validate the code, synthetic tests were conducted and the results indicate that it is possible to resolve both frequency- and depth-dependent attenuation values. The code was then applied to observed seismograms along the Leipzig-Regensburg fault zone. The fault zone was divided into a northern and southern area and the attenuation of the crust was calculated between 3 and 33 Hz. Our results demonstrate that the upper crust exhibits different characteristics compared to the middle and lower crust, as the intrinsic attenuation is dominant in the upper crust and significantly lower in deeper areas where earthquakes occur. In the mantle, the northern and southern regions also differ, with the southern part displaying stronger attenuation due to higher temperature.

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S03b - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Mapping the basement of the Cerdanya Basin (Eastern Pyrenees) using seismic noise methodologies

DOI: 10.57757/IUGG23-1995 - LINK

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[3]Karadeniz Technical University, o, Trabzon, Turkey

Ambient seismic noise acquired in the Cerdanya Basin (Eastern Pyrenees) is used to assess the capability of different methodologies to map the geometry of a small-scale sedimentary basin. We present results based on a 1-year long broad-band deployment covering a large part of the Eastern Pyrenees and a 2-months long high-density deployment covering the basin with interstation distances around 1.5 km. The explored techniques include autocorrelations, ambient noise Rayleigh wave tomography, horizontal to vertical spectra ratio, and band-pass filtered ambient noise amplitude mapping. The basement depth estimations retrieved from each of these approaches, based on independent datasets and different implicit assumptions, are consistent, showing that the deeper part of the basin is located in its central part, reaching depths of 600-700 m close to the Têt Fault trace bounding the Cerdanya Basin to the NE. The results from the different methodologies have an overall consistency, although significant differences appear in some zones. The results show also that when high-density seismic data are available, mapping the ambient noise amplitude in a selected frequency band is a valid tool to quickly map the sedimentary 3D geometry. Besides this methodological aspect, our results help to improve the geological characterization of the Cerdanya Basin and will provide further constraints to refine the seismic risk maps of an area of relevant touristic and economic activity.

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S03b - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Crustal scale radial anisotropic structure of northwestern India using ambient noise tomography

DOI: 10.57757/IUGG23-1083 - LINK

Santhoshkumar Gundu[1], *Satish Maurya*[1], *Mohan Gollapally*[1]
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We use ambient noise tomography to image the crustal-scale anisotropic structure beneath the Marwar craton of northwestern India to understand the impact of magmatism, crustal growth, and melt distribution. The study region was shaped by several magmatic events that include the Neoproterozoic Erinpura and Malani volcanism, Cretaceous Barmer-Sanchor rifting, and pre-Deccan volcanism. Correlograms of ~300 paths from 29 broadband seismic stations were computed for the vertical and transverse components. Rayleigh and Love wave group velocity dispersion curves of the fundamental mode were computed for the period ranging from 4s to 40s using the frequency-time analysis method. The 3D shear velocity tomography model was constructed by regionalizing the dispersion data to obtain local dispersion curves which were then inverted using a non-linear trans-dimensional Bayesian approach. The geometry of the Barmer-Sanchor rift is clearly delineated by an elliptical zone of low group velocity anomalies. The tomograms reveal low shear velocities (<3km/s) corresponding to thick sediments (~4km) in the rift. The crustal thickness beneath the rift varies from 30km to 34km while the region away from the rift has an average crustal thickness of 39km. The lower crust is characterized by high shear velocities ranging from 3.8km/s - 4.25 km/s that indicate magmatic underplating. Overall, the study region is characterized by positive radial anisotropy (~8%) that decreases away from the rift, crustal thinning beneath the rift, and a high velocity lower crust that reflects magmatic intrusion linked to rifting and magmatic events.

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S03b - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Seismic Velocity Constraints on the Characteristics, Origin and Evolution of the Blanco Transform Fault Zone, NE-Pacific

DOI: 10.57757/IUGG23-1364 - LINK

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Oceanic Transform Fault (OTF) systems have long been identified to play a crucial role in plate tectonics. However, comprehensive studies of their nature, origin and evolution have been hampered by their remoteness and sparse instrumentation. Morphological studies reveal OTFs as structurally and seismically complex zones characterized by physical segmentation, extensional basins, intra-transform spreading centers (ITSC), parallel to sub-parallel fault strands, etc. How this complexity is reflected in the crust and upper-mantle, and their tectonic implications have been hardly investigated tomographically. In this study, we use first-overtone Rayleigh waves extracted from ~1 year of ambient noise data recorded by 67 ocean-bottom seismometers to image the crust and uppermost mantle down to ~25 km beneath the ~350-km-long Blanco Transform Fault Zone (BTFZ) and adjacent oceanic plates. With the estimated phase velocity dispersion measurements (3.5-8.7 s), we inverted for phase velocity maps and then a 3-D shear wave velocity model. In general and in contrast to the adjacent oceanic plates, we imaged slow velocities along the BTFZ (velocity reduction reaching ~0.4 km/s) from surface to ~25 km depth. An actively deforming crust that opens and sustains pathways for enhanced hydrothermal circulation as indicated by recent local seismic studies that found abundant crustal seismicity along the BTFZ broadly explains this observation. Slower velocities observed in the mantle beneath the Blanco Ridge advocates for extensive serpentinization which might explain the recently documented mantle earthquake swarms linked with aseismic creep in this fault segment.

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S03b - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Correlated melting in the crust and uppermost mantle beneath the Hoh-Xil Basin, North Tibet inferred from ambient noise tomography

DOI: 10.57757/IUGG23-1829 - LINK

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How the Tibetan Plateau grew farther north from the India-Asia collision boundary has profound implications on the mechanics of continental deformation and accretion. The Hoh-Xil Basin in the northern Tibetan Plateau was once a foreland basin adjacent to the high-elevation proto-plateau until the Early Miocene and was rapidly uplifted since then. Here we collected 363 broadband seismic stations operated from 2007 to 2020, including 226 stations from five linear arrays mainly deployed in two north-south profiles across the core of the Hoh-Xil Basin with an average interstation distance of ~15 km. Based on Rayleigh wave signals extracted from ambient noise cross-correlations, we obtained more than 13000 dispersion curves and constructed a 3-D S-wave velocity (V_S) model using measurements in 6–65 s periods by the direct inversion method. Our model shows significant lateral variations of V_S in the crust and uppermost mantle from the southern to the northern Tibetan Plateau, which should reflect different melt fractions according to the theoretical seismic velocity-melt fraction relationship. We observe widespread partially molten crust in the northern Tibetan Plateau but only isolated pockets in the south manifested as low-V_S anomalies in the middle-lower crust. The spatial correlation of these low-V_S anomalies with strong uppermost mantle low-V_S anomalies and young crust-/mantle-derived magmatism in the Hoh-Xil Basin suggests that the plateau grew through magmatic intrusion and accretion induced by the asthenospheric upwelling due to lithospheric mantle removal. These findings lead to implications for the role of delamination-driven magmatism in the continental crust growth in collision orogens.

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S03c - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Two thin middle-crust low-velocity zones imaged in the Chuan-Dian region of Southeast Tibet and their tectonic implications

DOI: 10.57757/IUGG23-2282 - LINK

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[3]Chinese Academy of Sciences, Innovation Academy for Earth Science, Beijing, China

Intra-crustal low-velocity zones (LVZs), indicating the mechanically weak crust, are widely observed in Southeast Tibet but remain controversial. New constraints on LVZs in this area are obtained from a joint inversion of receiver functions and Rayleigh wave dispersion using a newly deployed linear seismic array. Our shear-wave velocity model reveals two isolated LVZs (~3.5 km/s) in the middle crust at almost the same depth (~30-40 km) wrapping around the rigid Daliangshan sub-block. Combined with previous observations, the two middle-crust LVZs may attribute to the crust materials transporting from the central Tibetan Plateau to its southeast margin. The mechanically weak LVZs in the middle crust might imply decoupling between the upper and lower crust. We speculate that the middle crustal flow model plays a major role in the southeastern margin of the Tibetan Plateau accommodating the deformation caused by the collision between the Indian and Eurasian plates.

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S03c - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Crustal structure beneath northern Myanmar from ambient noise tomography

DOI: 10.57757/IUGG23-2393 - LINK

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The Burmese arc consists of the Indo-Burman Ranges (IBR), an accretionary wedge in the west and the Central Myanmar Basin (CMB) in the east. It is bounded in the east by the seismically active Sagaing Fault to the Shan Plateau. Intermediate-depth seismicity below Myanmar occurs at depths up to ~150 km, generally understood to be related to the subducting Burma slab. We use ambient noise tomography to construct a regional three-dimension (3-D) shear wave velocity model, aiming at figuring out the transition from oceanic subduction to continental subduction/collision along the Burmese arc and how it affects the upper plate crustal deformation. Our dataset includes 30 seismic stations from a recently deployed temporary seismic array and ~50 permanent stations in and around Myanmar. Ambient noise corss-correlations are calculated at periods of 5-60 s and are inverted for a 3-D velocity model from the crust to the uppermost mantle. Our model shows a low-velocity anomaly extending to >20 km depths beneath the northern part of the CMB that accurately defines the Chindwin Subbasin. The crust beneath the IBM is characterized by low velocity, which probably reflects the fluid-rich accreted sediments that has experienced metamorphism in the mid-lower crust. Underneath the Sagaing Fault an N-S trending high-velocity anomaly is clearly visible at depths of 40-70 km in the uppermost mantle extending from 20°N to 24°N. The anomaly could represent a remnant slab of the Incertus Arc collision/subduction and mark the eastern boundary of the Burma plate.

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S03c - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Ambient noise-based eikonal tomography in a deeply incised, sediment-filled canyon (Rhône valley, France) using a dense array of seismic nodes

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Common ambient noise tomography studies use straight ray tomography for deriving group or phase velocity maps from long-term cross correlation of station pairs. Being suitable for low frequencies and large inter-station distances, this simplification can be problematic in near-surface studies where higher frequencies are considered and stronger lateral velocity variations are encountered. The eikonal tomographic approach avoids the assumption of straight rays by computing local group or phase velocities from the gradient of the traveltimes measured between the virtual sources and receivers, therefore approximating the true propagation trajectories of surface waves. In this work, we applied the eikonal approach to data from a dense, one-month long seismic deployment consisting in 400 3-component nodes installed over a 10x10 km zone in the heavily industrialized area of the Tricastin Nuclear Site (Rhône valley). This area is located above a sediment-filled, deeply incised canyon dug during the Messinian Salinity Crisis. The extreme subsurface topography of this canyon makes this area an interesting target for an eikonal tomographic study. We implemented an automated method that measures the phase traveltimes of the fundamental mode of Rayleigh and Love waves from the ambient noise cross correlations' phase spectra. We then applied the eikonal approach to the measured traveltimes, resulting in a set of phase velocity maps for Rayleigh waves that are in good agreement with the existing geological knowledge and cover a frequency range from 0.4 to more than 5 Hz.

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Long-distance Pdiff Coda from whole-mantle scattering observed at high frequencies

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The observation of main seismic phases reaching the core shadow beyond 100º is known to traverse through the core of the Earth like PKP or PKiKP waves. Besides these, Pdiff wave that diffracts along the Core-Mantle Boundary (CMB) can also propagate into the core shadow. PKP is not the first wave that arrives in the shadow zone. Scattering of PKP at the CMB or in the whole mantle creates precursors to PKP arriving a few seconds before the actual PKP arrival. However, the scattering of P waves in the whole mantle allows waves to arrive more than 100 s prior to the PKP precursor if they do not enter the core but scatter around it through the fast mantle material. This energy arrives after the theoretical arrival of the Pdiff phase appearing to be the coda of Pdiff. We studied high-frequency (1-2 Hz) seismogram stacks of several large magnitudes (≥ 7.9 Mw) earthquakes. Individually Pdiff coda can be observed at very long distances beyond 150° in these events and deeper events allow for more clean observations. The Monte Carlo method is used to simulate the global earthquake scattering in a 1D spherically symmetric heterogeneous model. Simulation in an independently derived model of heterogeneity matches the observation of the Pdiff coda. An analysis of the origin of Pdiff coda is discussed using simulations with different scattering layers from the lithosphere to CMB. We demonstrate that the single scattering in the whole mantle explains the essential features of the observed Pdiff coda.

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Imaging Absorption and Heterogeneity Using Adjoint Envelope Tomography

DOI: 10.57757/IUGG23-4208 - LINK

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Seismic and ultrasound tomography can provide rich information about spatial variations of elastic properties inside a material rendering this method ideal for geophysics and nondestructive testing. These tomographic methods primarily use direct and reflected waves, but are also strongly affected by waves scattering at small scale structures below the resolution limit. As consequence conventional tomography can unveil the deterministic large scale structure only, rendering scattered waves imaging noise. With Adjoint Envelope Tomography (AET) we propose a mathematically rigorous tomographic approach to image the distribution of small scale heterogeneity and absorption. AET is based on a forward simulation of energy propagation using Radiative Transfer Theory to synthesize seismogram envelopes and an adjoint (backward) simulation of the envelope misfit to obtain the gradient for iterative model updates -- in full analogy to full-waveform inversion (FWI). We present the mathematical concept, technical aspects of the simulations and applications of the approach to numerical experiments and an ultrasound experiment in a metric size concrete specimen. The trade-off between the quality factor Q used to quantify intrinsic attenuation and the fluctuation strength ε representing the characteristics of the heterogeneity reflects the similarity of the effects of absorption and scattering have on ballistic waves. We discuss a strategy to reduce the effect of this trade-off in the application of AET by using dedicated time windows for the imaging of both properties.

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Seasonal changes in shallow earth structure in the permafrost region of Alaska

DOI: 10.57757/IUGG23-0351 - LINK

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We analyzed data from the EarthScope Transportable Array in Alaska in order to understand the nature of near-surface melting in the permafrost region. Data consisted of (1) temperature, (2) vertical seismic data, (3) horizontal seismic data, and (4) wind data. Observations at some stations indicate a rapid melting phenomena in the summer that causes a thousandfold increase in horizontal power spectral density. This rapid rise in horizontal seismic noise typically occurs in July, lasting about 30 days. The initiation of this major melting period does not happen immediately after the surface temperature exceeds 0^{o}C; instead, there is a delay of about a month. After the peak horizontal amplitude is reached, it gradually returns to the pre-melting level. Many stations show that this return occurs by December. However, some stations require until March or April in the following year to arrive back to their pre-melting level. For all stations, this return occurs well after the surface temperature becomes negative in September or October. This suggests that the melt layer remains at depth as surface temperatures drop below freezing, perhaps sandwiched between the developing ice from the surface and the underlying permafrost ice. However, we noted some caution is required at a few stations because a transient surge in horizontal amplitudes occurs in February and November that appears to be correlated with winds. We summarize the temporal characteristics of individual stations, their seasonal geographic patterns throughout Alaska and a potential mechanism to explain a sudden increase of horizontal noise.

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The relationship between seismic noise energy excited by a streamflow and water level revealed from spectral analysis of Hi-net seismograms

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Vibrations induced by a streamflow are major component of seismic ambient noise. They stand out in seismograms especially in the upstream basins, where the flow speed is high and the amount of cultural noise is low. In hydrological point of view, real-time monitoring of river discharge and water depth in the upstream basin is essentially important for early forecast of flooding. However, in-situ monitoring of streamflow is extremely difficult in the upstream basin due to poor accessibility and complexly distributed tributaries in rough terrains. Therefore, a new tool is demanded for remotely monitoring of flow conditions in the upstream basins. The use of seismic noise will be a good candidate for this purpose (e.g., P.C. and Sawazaki, 2021).

In this study, we compared records of Hi-net seismograph and water-level observation in northeastern Japan. The target period is from October 10 to 17, 2019, when the 2019 Typhoon Hagibis passed through eastern Japan. After clipping transient signals such as earthquakes from the Hi-net seismograms, we computed envelopes of the seismogram in the frequency ranges of 2 Hz to 32 Hz. Then we compared them with the water level records located in the same river basins.

As a result, we found that correlation between the seismogram envelope and the water level tends to be higher in higher elevation areas. By fitting the two observables with a power-law relationship, we found that the water level is roughly proportional to the 0.2 to 0.6 power of the noise energy.

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Q-coda from ambient noise cross-correlation: A new volcano monitoring technique?

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Time-lapse monitoring of seismic velocity at a volcanic area can provide important information about the dynamics of the volcanic system and its temporal variability. One standard technique to monitor small changes in the medium is ambient noise interferometry. This technique is based on quantifying relative velocity variations (dv/v) by measuring changes in the ambient noise cross-correlation signal phase. In this study, we demonstrate that together with velocity variations, the study of changes in seismic attenuation (Qc) extracted from ambient noise cross-correlation could be relevant for volcano monitoring.
The Qc is determined using the lapse-time dependence method (Calvet and Margerin, 2013), in which, Qc is measured as a function of the coda window length for different onsets of the ambient-noise cross-correlation coda. We apply this technique to the 2021 Cumbre Vieja eruption in La Palma (Canary Islands), which started on Sept. 19th and had a significant social and scientific impact. First, we determine a reference Qc model of the Cumbre Vieja volcano using data from Aug. 1st to 31st, 2021. Then, we analyze the spatio-temporal Qc variations during the nineteen days preceding the eruption, and we compare our results with previously obtained dv/v results. We observe an increase of Qc during the pre-eruptive phase, corresponding to a dv/v decrease. We hypothesize that the observed correlated Qc increase and dv/v drop could be explained by the ascent of hydrothermal fluids towards the surface before the eruption.

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Capability of monitoring for the change in shallow ground structure by highly stable vibration sources

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Capability of highly stable vibration source, which is named ACROSS, that we have used is evaluated for monitoring near surface ground structure. Near-surface change in ground structure due to environmental effect is often observed, because near surface part is sensitive to the environmental change such as strong ground shaking, rain fall, ground water level, and atmospheric temperature. Effect of strong ground shaking was found in the experiment in Awaji (Ikuta et al. 2002) and interpreted as opening of preferred oriented cracks and water penetration with the change in seismic velocity (Ikuta and Yamaoka,2004) and amplitude (Tsuji et al., 2022). These findings are attributed to a simple configuration of source and receivers, in which receivers are deployed about 1000m below the source. Effect of atmospheric temperature is also found in this site and can be attributed to the change in the energy dissipation in the shallow part. Effects of rain and ground water are investigated in Suzuki et al. (2021) using both P and S wave simultaneously. Different response is found between seasonal change and short-term change after raining. Seasonal change can be interpreted as the change in crack density and saturation, but short-term change can be interpreted as micro-scale mixture of water and air in fractures. Oba et al (2022) found a clear response to rain fall in later arrivals of vibration signal observed by a seismic array of about 2km from the source. These finding shows the capability to distinguish variety of penetration of ground water with vibration source.

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Illuminating the non-linear relationship between volcanic, tectonic, and environmental forcings and the seismic velocity by analysis of interdisciplinary datasets

DOI: 10.57757/IUGG23-1472 - LINK

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[3]*University of Washington, Department for Earth and Space Sciences, Seattle, USA*

Quantifying Changes in the seismic velocity (*dv/v*) from repeating sources or ambient noise surveys is an established tool in seismology. *dv/v* has been shown to correlate to a multitude of parameters such as stress variations, pore pressure changes, and modifications in the microscopic and macroscopic integrity of the sampled medium (i.e., “damage”). In turn, these parameters are impacted by an even greater number of mechanisms, for example, precipitation, temperature, surface loading, seismic activity, hydrology, volcanic activity, or tidal forces. However, their relationships to *dv/v* are often non-linear, hard to quantify, and poorly understood. Additionally, for “field data”, it can be challenging to decipher the contribution of each individual parameter to *dv/v* changes. In this work, we analyse continuous seismic data and interdisciplinary datasets from Mt St Helens (USA) and the Kamchatka peninsula (Russia) to illustrate the diversity of mechanisms impacting dv/v and discuss potential strategies to unravel the observations. We show that, for volcanic areas in particular, analysing *dv/v* is a complex task due to the addition of volcanic activity, high-relief topography, and strongly heterogeneous subsurface structures.

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Surface wave monitoring using ambient noise for detecting temporal variation of underground structure of landslide

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Temporal variation of shallow subsurface structure is monitored by the SPAC-based method using a seismic array on a landslide area. We deployed a seismic array that consists of 14 three-component seismometers with a natural frequency of 4.5Hz on flat ground with diameters of 28m x 75m in a landslide area in the western part of Shizuoka prefecture, Japan. We used the data from October 2020 to May 2022.
We applied the SPAC method using ambient noise data. The SPAC is obtained for each day and temporal variations are investigated. We compared the daily SPAC with the reference SPAC, which is obtained by stacking all the daily SPAC. The results show a characteristic change in SPAC that includes weekly changes, rainfall-related changes, and seasonal changes. In the weekly changes, a systematic difference is found between weekends and weekdays. Regarding the rainfall-related change, the large vibration, which has a significant impact on SPAC analysis, by a stream near the array is often observed during/after heavy rain. We statistically estimated and removed the effect of these two changes to monitor the variation due to the subsurface structure. We found the SPAC in the high-frequency region decreases due to rainfall, which is regarded as being due to a rise in the groundwater level caused by rainfall. MMSPAC (multimode spatial autocorrelation) method (Asten.2006, Ikeda.2012) is used to estimate the most strongly affected depth ranges to compare the structure model using reference SPAC. The seasonal change may be associated with the state of the shallow groundwater.

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Temporal variations of seismic velocities from ambient noise: monitoring groundwater in the Maltese islands

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The Maltese islands, approximately 314 km^2 in area with a high population density, face high levels of water stress due to low amounts of rainfall and a dependence on groundwater abstraction. Until now, *in-situ* borehole readings have been the only method utilised to monitor the quantitative status of groundwater in the Maltese islands. This study investigates an innovative, cost-effective approach to groundwater monitoring in a small island environment by computing cross-correlations and autocorrelations of ambient seismic noise recorded on seismic networks of broadband and short-period stations in the Maltese islands. We compare the borehole readings of groundwater levels ranging from 0.28-3.39 m above mean sea level with the variations in seismic velocity ($\delta v/v$). We apply appropriate filters for the broadband and short-period stations of 0.1-1 Hz and 0.3-3 Hz, respectively. The results demonstrate clear seasonal changes in the seismic velocities, which can be correlated with changes in groundwater levels in nearby boreholes. We find that variations of the $\delta v/v$ from autocorrelations are more pronounced than the cross-correlation, with maximum seismic velocity changes of ~2% and ~0.3% respectively. The quality of the $\delta v/v$ deteriorates at longer interstation distances where seasonal variations are less noticeable. Presumably, this is because longer interstation paths tend to traverse more complex geology, different types of aquifers, or even the sea.

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Temporary variation of shallow groundwater level derived from cultural noise interferometry in southern Longitudinal Valley, Taiwan

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We have computed the cross-correlation functions (CCF) of the cultural noise to measure the temporal variation in seismic velocity for each station pair among the local Chihshang array in Taiwan, which was deployed in 2013-2020. A significant seasonal variation of asymmetric CCFs in the frequency band of 2-8 Hz, which is supposed to be the cultural noise, has been identified in this study. We further extract the velocity change (δv/v) by using the stretching method with the largest value up to 12% and found that the δv/v highly correlates with the nearby shallow groundwater level (GWL) fluctuation that usually occurs from September to November after rain season every year. On the other hand, the temporal variation of δv/v can only be observed for coda CCF with frequency higher than 3 Hz, which indicates that the source depth is within 30 m in the near surface layer based on its corresponding sensitivity kernel. The station pairs along the eastern side of Longitudinal Valley present smaller amplitude of δv/v, which may reflect a reduced GWL fluctuation in this region. Even though there is a clear 1-month lag between the rainfall and the GWL, there is no phase delay between the time series of the observed δv/v and the GWL. Our results suggest that we are capable of quantitatively monitoring the transient groundwater storage by a analyzing the cultural noise cross correlation functions in the Chihshang area, where is covered with a thick gravel bed in the southern Longitudinal Valley.

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S03e - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Inspecting tidal signals observed by passive image interferometry

DOI: 10.57757/IUGG23-3065 - LINK

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Solid Earth is subjected to nanostrain tidal deformations caused by gravitational attraction of the Moon and Sun. This causes periodic deformations of imperceptible fractures in the shallow rock that likely result into subtle variations of seismic velocities. It is possible to theoretically model the gravitational tidal deformations while the seismic velocities can be estimated, e.g., using ambient noise recordings processed with passive image interferometry. Combining these two pieces of information could allow for in-situ assessment of bedrock properties beneath seismic stations. In this study, we tried to accomplish this task using 18 standalone seismic stations (i.e., no array) from a network of the Integrated Plate Boundary Observatory Chile, complemented by several others in Europe and in the Americas. The velocity changes were mostly estimated with seismic recordings filtered in 1-4 and 4-7 Hz bands, using hourly Green's functions acquired after temporal stacking. Analysed coda lapse time windows of the Green's functions were 1-6, 5-10 and 8-13 seconds. Tide-related velocity changes were observed (mostly the M2 component). However, our results show that observability of such tide-related velocity variations seems to be strongly related to the station proximity to oceanic coastlines. This raises reasonable doubt about the required solid Earth tides origin of the observed tidal signals.

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S03e - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

SANS: Daily Global Seismic Ambient Noise Source Maps

DOI: 10.57757/IUGG23-1857 - LINK

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With amplitude and full-waveform based ambient noise tomography and monitoring methods on the horizon, knowledge of the underlying noise source distribution is vital to avoid possible misinterpretations, e.g., in terms of time-varying Earth structure. Particularly the oceanic microseisms have strong spatio-temporal variations on multiple scales which could influence full waveform or travel time measurements if not taken into account properly. In this work, we present daily Seismic Ambient Noise Source (SANS) maps of the secondary microseisms (0.1 to 0.2 Hz) on a global scale which are made available to the public here: sans.ethz.ch (Igel et al., 2022).

The computation of daily global SANS maps is possible due to recent improvements of non-linear finite-frequency noise source inversion methodology including pre-computed wavefields and spatially variable grids (Igel et al., 2021). Furthermore, by introducing an initial model from a different noise source imaging method - Matched Field Processing (MFP) - we accelerate the convergence of the inversion and improve the final maps. In collaboration with the Swiss National Supercomputing Centre (CSCS), we are able to run daily global SANS inversions which can be viewed, downloaded, and implemented into other studies. This paves the way for future full waveform ambient noise source and structure inversion workflows.

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Tracking a Vibroseis Truck using 6 Rotational Sensors in Fürstenfeldbruck, Germany

DOI: 10.57757/IUGG23-3186 - LINK

Gizem Izgi[1], *Eva Eibl*[1], *Frank Krüger*[1], *Felix Bernauer*[2]
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Six degree-of-freedom (6-DoF) ground motion measurements are recorded combining a rotational sensor and a seismometer. This allows in principle to determine the back azimuth of a moving source using a single point measurement. We investigated the movement of a vibroseis truck operated from 20 November 2019, 11:00 UTC to 21 November 2019, 14:00 UTC. We used 480 Sweep signals each lasting 15 seconds in a broad frequency range between 7 to 120 Hz from 160 different locations. We derived back azimuths for each sweep from 6 DoF data and calculated root mean square amplitudes of each ground rotation component. We repeat this procedure for 5 other nearby rotational sensors of the same type. Within the first day, the North pointing rotation axis of all sensors recorded larger amplitude signals at the beginning of the experiment proving that SV shear wave energy is dominant. Later, we observed larger amplitudes on the East component following the direction of the moving vibroseis truck. Conventional methods to locate a seismic source rely on the P wave polarization or arrival times measured with a network of stations. In this study we used S waves to track the vibroseis truck movements since rotational sensors are not sensitive to P wave motions.

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S04a - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Monitoring construction and quarry blasts with Raspberry Shakes and machine learning tools in the city of Oslo, Norway

DOI: 10.57757/IUGG23-1432 - LINK

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The increase in urban population has caused many cities to upgrade their infrastructures and embrace the vision of a "smart-city". This endeavour relies on sensor data providing relevant information for local authorities and the general public. Our study is part of a project to evaluate different types of geodata and machine learning (ML) tools for this purpose, focusing on the city of Oslo, Norway. We aim to collect information about any kind of unusual event that produces a seismic signature, e.g., explosions or sudden mass movements, to facilitate fast emergency response. Furthermore, there is ongoing construction of tunnels and under-ground water storage facilities under populated areas in Oslo, activities which are accommodated by blasts felt by citizens. A challenge with seismic records from urban areas is the presence of a multitude of sources and high background noise level, requiring advanced processing methods. We use seismic data recorded on 10-12 Raspberry Shake sensors to quickly detect, classify, and locate urban seismic events, blasts in particular. We present a ML approach to first identify rare events and then build an automatic classifier from those templates. For the first step, we employ an outlier detection method using autoencoders trained on the continuous background noise. Badly reconstructed signals are identified as outliers and located using their surface wave (Rg) signatures on the seismic network. From several blast areas we select a cluster with most activity and train a supervised classifies using a Convolutional Neural Network to detect similar events.

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S04a - Advancements in Acquisition, Processing and Interpretation of Seismological Data

The UPFLOW experiment: new observations from a ~1,500 km aperture array of 49 ocean bottom seismometers in the mid-Atlantic

DOI: 10.57757/IUGG23-3187 - LINK

Ana Ferreira[1], Miranda Miguel[2], Maria Tsekhmistrenko[1], Upflow Team[3]
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[3]UPFLOW, Upflow, Europe, United Kingdom

Constraining upward mantle flow is crucial to understand global mantle flow and directly link the Earth's interior with the surface. However, mantle upwellings that connect the deep mantle to the surface are poorly understood. The goal of the UPFLOW project (https://upflow-eu.github.io) is to develop new high-resolution seismic imaging methods along with new data collection to greatly advance our understanding of upward mantle flow. UPFLOW deployed 50 and recovered 49 ocean bottom seismometers (OBSs) in a ~1,000×2,000 km^2 area in the Azores-Madeira-Canaries region starting in July 2021 for ~13 months, with an average station spacing of ~150-200 km. The experiment included institutions from five different countries: Portugal (IPMA, IDL, Univ. of Lisbon, ISEL), Ireland (DIAS), UK (UCL), Spain (ROA) and Germany (Potsdam University, GFZ, GEOMAR, AWI). Most of the instruments had three-component wideband seismic sensors and hydrophones, but three different designs of OBS frames were used. Our analysis shows high-quality data, notably a substantial noise decrease in vertical component long-period data (T>~30s). We show illustrative recordings of teleseismic, local events and non-seismic signals (whales, ships, Tonga eruption), as well as systematic analyses of the background noise levels, clock skew and horizontal component rotation angles.

UPFLOW team: Ana MG Ferreira, Miguel Miranda, Sameneh Baranbooei, Roberto Cabieces Diaz, Mafalda Carapuço, Carlos Corela, José Luis Duarte, Henrique Ferreira, Wolfram H. Geissler, Katrina Harris, Stephen Hicks, Kasra Hosseini, Frank Krueger, Dietrich Lange, Afonso Loureiro, Peter Makus, Augustin Marignier, Marta Neres, Luis Ramos, Theresa Rhein, Alex Saoulis, David Schlaphorst, Frederik Tilmann, Maria Tsekhmistrenko, Kuan-Yu Ke.

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Eifel Large-N Experiment: Detection and Localization of Seismic Events using Stacking and Migration Approach combined with Neural Network Phase Characterization

DOI: 10.57757/IUGG23-4193 - LINK

Marius Paul Isken[1,2], Miriam Reiss[3], Simone Cesca[1], Martin Hensch[4], Bernd Schmidt[5], Torsten Dahm[1,2], Jannes Münchmeyer[6]
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[2]University of Potsdam, Institute for Geosciences, Potsdam, Germany
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[4]Erdbebendienst Südwest,
Regierungspräsidium Freiburg Landesamt für Geologie- Rohstoffe und Bergbau, Freibug, Germany
[5]Landesamt für Geologie und Bergbau- Rheinland-Pfalz,
Referat Ingenieurgeologie und Erdbebendienst, Mainz, Germany
[6]Université Grenoble Alpes- Université Savoie Mont Blanc, CNRS- IRD- IFSTTAR- ISTerre, Grenoble, France

We present the detection and localization of local seismic events from a seismic network consisting of more than 350 short-period and broadband stations deployed in the Eifel volcanic region, centered around the Laacher See. The network spans an area of 180 km by 120 km. Using a combination of stacking and migration method and characteristic function generated by a re-trained neural network which are imaging P and S wave phase arrivals, we are able to detect and automatically locate seismicity in the network from continuous waveform data, including those events associated with dormant volcanic processes. The Eifel region has been geologically active for millions of years, with the most recent volcanic explosive eruption 13,000 years ago at the Laacher See. While the area is currently considered volcanic dormant, the ongoing seismic activity provides insight into the magmatic activity at depth. Our results can help to improve our understanding of the transcrustal magmatic system beneath intraplate volcanic fields and potential for future volcanic activity in the Eifel. The method and example presented here can be applied to volcanic provinces elsewhere support volcanic monitoring and fast, automatic processing of seismicity.

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S04a - Advancements in Acquisition, Processing and Interpretation of Seismological Data

On-Fault Micro-Seismic Monitoring with Multiple Acoustic 3D Arrays: Insights from the Bedretto Underground Lab

DOI: 10.57757/IUGG23-2110 - LINK

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Accurate hypocentre parameters are crucial but challenging for characterising underground rock deformation. Microseismicity can reflect the small-scale deformation processes that occur before, during and after larger earthquake ruptures. The Fault Activation and Earthquake Rupture (FEAR) project will execute controlled fault stimulation experiments on the 50-100 metre scale at the Bedretto Underground Lab, an in-situ test bed with a granitic overburden of more than 1000 metres. The main objective of the FEAR project is to monitor earthquake rupture processes in the fault zone, and to better understand the microphysical rupture processes.

Until the full monitoring system is completed, most of our seismic sensors are located along the Bedretto tunnel. This non-optimal network geometry leads to large hypocentre location uncertainties. To best monitor seismic activity in the target volume, we develop an alternative monitoring method that uses beamforming from four miniature 3D arrays tetrahedral deployed above the tunnel. Using four acoustic emission sensors with the apertures ranging from 0.7 to 1.5m, each 3D array is capable of detecting weak and very high frequency (up to 100 kHz) signals.

We use synthetic data to show that earthquake hypocentres can be accurately estimated with back-projection, by combining four array beams. We test and calibrate the array method using seismic signals from controlled sources during an active seismic campaign. Tetrahedral arrays will form an important part of the integrated FEAR monitoring system, which includes on-fault to regional measurements, using acoustic emissions and accelerometers, fibre-optic cable network, fluid flow and hydro-bio-chemical monitoring.

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S04a - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Spatial b-value distribution based on Gaussian process inference using a geological prior with focus on California and Turkey

DOI: 10.57757/IUGG23-4748 - LINK

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As a population parameter, reliable estimation of the b-value is intrinsically complicated, particularly when spatial variability is considered. We approach this issue by treating the spatial b-value distribution as a non-stationary Gaussian process for the underlying earthquake-realizing Poisson process. For Gaussian process inference the covariance—which describes here the spatial correlation of the b-value—must be specified a priori. We base the covariance on the local fault structure, i.e. the covariance is anisotropic: elongated along the dominant fault strike and shortened when normal to the fault trace. This adaptive feature captures the geological structure better than an isotropic covariance or similarly defined and commonly used running-window estimates of the b-value.

We demonstrate the Bayesian inference of the Gaussian process b-value estimation for two regions: California based on SCEDC earthquake and Turkey based on the AFAD earthquake catalog. The covariances in the inferences are calibrated with the SCEC community fault model the GEM fault model for California and Turkey, respectively.

Our model provides a continuous b-value estimate (including its uncertainties) which reflects the local fault structure to a very high degree. We are able to associate the b-value with the local seismicity distribution and link it to major faults. In light of the recent Turkish earthquake sequence, we also assess the temporal evolution of the b-value of recent seismicity before and after major events.

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S04b - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Constraining earthquake depth at teleseismic distance: Picking depth phases with deep learning

DOI: 10.57757/IUGG23-4563 - LINK

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Automated teleseismic earthquake monitoring is an essential part of global seismicity analysis. However, while constraining earthquake epicenters in an automated fashion is an established technique, constraining event depth is substantially more difficult, especially in the absence of nearby stations. One solution to this challenge are teleseismic depth phases but these can currently not be identified by automatic detection methods. Here we propose two deep learning models, DepthPhaseNet and DepthPhaseTEAM to detect depth phases. The first model closely follows the PhaseNet architectures with minor modifications; the latter allows joint analysis of multiple stations by adding a transformer to this basic architecture. For training the models, we create a dataset based on the ISC EHB bulletin, a high-quality catalog with detailed phase annotations. We show how backprojecting the predicted phase arrival probability curves onto the depth axes yields excellent estimates of earthquake depth. The models achieve mean absolute errors below 10 km. Furthermore, we demonstrate that the multi-station model, DepthPhaseTEAM, leads to better and more consistent predictions than the single-station model DepthPhaseNet. To allow direct application of our models, we integrate them within the SeisBench library for machine learning in seismology.

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Detection of deep low-frequency tremors from past paper records at a station in southwest Japan based on convolutional neural network

DOI: 10.57757/IUGG23-1600 - LINK

Ryosuke Kaneko[1], Hiromichi Nagao[2], Shin-ichi Ito[2], Hiroshi Tsuruoka[2], Kazushige Obara[2]
[1]The University of Tokyo, Graduate School of Information Science and Technology, Tokyo, Japan
[2]The University of Tokyo, Earthquake Research Institute, Tokyo, Japan

Since deep low-frequency tremors are considered to be associated with large earthquakes that occur adjacently on the same subducting plate interface, it is important to investigate tremors that occurred before the establishment of modern seismograph networks such as the High Sensitivity Seismograph Network (Hi-net). We propose a deep-learning solution to detect evidence of tremors in the scanned images of paper seismogram records from over 50 years ago. In this study, we fine-tuned a convolutional neural network (CNN) based on the Residual Network (ResNet), pre-trained based on images of synthetic waveforms in our previous study, using a dataset comprised of images generated from real seismic data recorded digitally by Hi-net to facilitate a supervised analysis. The fine-tuned CNN was able to predict the presence or absence of tremors in the Hi-net images with an accuracy of 98.64%. Gradient-weighted Class Activation Mapping (Grad-CAM) heatmaps created to visualize model predictions indicated that the CNN's ability to detect tremors is not degraded by the presence of teleseisms. Once validated using the training images, the CNN was applied to paper seismograms recorded from 1966 to 1977 at the Kumano observatory in southwest Japan, operated by Earthquake Research Institute, The University of Tokyo. The CNN showed potential for detecting tremors in scanned images of paper seismogram records from the past, facilitating downstream tasks such as the creation of new tremor catalogs. However, further training using an augmented dataset to control for variables such as inconsistent plotting pen thickness is required to develop a universally applicable model.

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creation of new tremor catalogs. However, further training using an augmented dataset to control for variables such as inconsistent plotting pen thickness is required to develop a universally applicable model.

Seismic-phase detection using multiple deep learning models for global and local representations of waveforms

DOI: 10.57757/IUGG23-1282 - LINK

Tomoki Tokuda[1], *Hiromichi Nagao*[1,2]
[1]*The University of Tokyo, Earthquake Research Institute, Tokyo, Japan*
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The detection of earthquakes is a fundamental prerequisite for seismology and contributes to various research areas. Recent advances in machine learning technologies have enabled the automatic detection of earthquakes from waveform data. In particular, various state-of-the-art deep-learning methods have been applied to this endeavor. In this study, we proposed and tested a novel phase detection method employing deep learning, which is based on a standard convolutional neural network in a new framework. The novelty of the proposed method is its separate explicit learning strategy for global and local representations of waveforms, which enhances its robustness and flexibility. Prior to modelling the proposed method, we identified local representations of the waveform by the multiple clustering of waveforms, in which the data points were optimally partitioned. Based on this result, we considered a global representation and two local representations of the waveform. Subsequently, different phase detection models were trained for each global and local representation. For a new waveform, the overall phase probability was evaluated as a product of the phase probabilities of each model. This additional information on local representations makes the proposed method robust to noise, which is demonstrated by its application to the test data. Furthermore, an application to seismic swarm data demonstrated the robust performance of the proposed method compared with those of other deep learning methods. Finally, in an application to low-frequency earthquakes, we demonstrated the flexibility of the proposed method, which is readily adaptable for the detection of low-frequency earthquakes by retraining only a local model.

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S04b - Advancements in Acquisition, Processing and Interpretation of Seismological Data

A novel application of deep learning in extracting Earth's free oscillation

DOI: 10.57757/IUGG23-1398 - LINK

Shiyu Zeng[1], Rumeng Guo[1], Binbin Liao[1], Kun Dai[1], Yijun Zhang[1], Xiaoming Cui[1], Jiangcun Zhou[1], Jianqiao Xu[1], Xiaodong Chen[1], Mingqiang Hou[1], Heping Sun[1]
[1]Chinese Academy of Sciences,
Innovation Academy for Precision Measurement Science and Technology, Wuhan, China

The normal modes (i.e. Earth's free oscillations) are long-period low-frequency seismic signals, which are excited by a variety of factors, such as earthquakes, volcanic eruption, landslide, avalanche and so on, are an essential vehicle for global seismic tomography to elucidate large-scale heterogeneities within the deep Earth. Accurate extraction of signals on normal mode spectrum is a prerequisite for the imaging inversion, providing the differences between the observed and synthetic normal mode spectrum. However, the normal mode spectrum has great complexity due to many structural factors within the Earth, so unacceptable false and dismissed selections of the signals always occur, which hinder the development of exploration of the deep Earth's deep interior based on normal mode data. To address these problems, we build a deep-learning based neural network, named ModeNet, which is capable of precisely and efficient selecting the frequency windows to cover the target normal modal signals on a noisy spectrum, which could outperform the conventional spectrum-FLEXWIN method without relying on comparisons with synthetics. We also define our own method to evaluate the performance of ModeNet on the testing set and obtain a precision as high as ~0.98. Moreover, ModeNet achieves good generalization in processing seismograms of different events with different noise levels, components, and time window data, as well as superconductivity-gravimeter observations. Therefore, ModeNet could be implemented as a valuable tool for the future deep Earth inversion.

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S04c - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Source and spectral characteristics of ordinary and low-frequency earthquakes inferred from the probabilistic analysis of 10-year large data sets

DOI: 10.57757/IUGG23-4419 - LINK

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[1]Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Roma, Italy
[2]ERI, Earthquake Research Institute, Tokyo, Japan

We analyze two large data sets of 10 years (2009-2018) of ordinary earthquakes (OEs) detected in Italy by INGV and low-frequency earthquakes (LFEs) detected in Japan by JMA. We estimate the joint probability density function of seismic moment (M0) and corner frequency (fc) from S-wave displacement spectra. We use unfiltered signals and manually revised S-wave arrival times.

We estimate a wide range of moment magnitudes (Mw = 0-6 for OEs, 0.5-2.5 for LFEs) and observe a self-similar scaling between M0 and fc for both OEs and LFEs with a constant stress-drop of ~MPa and ~kPa, respectively. However, OE spectra show a constant corner frequency fc* ~10 Hz for Mw <~ 2.5. We refer fc* to the cut-off frequency of the medium anelastic attenuation, acting as a low-pass filter and producing an apparent corner frequency that does not scale with the earthquake source (M0).

Conversely, for the same Mw <~ 2.5, LFEs exhibit fc between 1 and 8 Hz that scale with M0, showing that their low-frequency content is a real source characteristic and not an apparent consequence of anelastic attenuation.

Finally, both OEs (for Mw <~ 2.5) and LFEs show a systematic underestimation of local magnitude when compared with moment magnitude, that we analytically explain as a consequence of anelastic attenuation (fc*) for OEs and of low stress-drop (~kPa) for LFEs.

Our method allows the use of raw earthquake waveforms to infer robust information both for monitoring purposes and for physical interpretations of the earthquake source in different tectonic settings and at different scales.

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S04c - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Automated source parameters assessment for mining induced seismicity

DOI: 10.57757/IUGG23-3357 - LINK

Jakub Kokowski[1], *Grzegorz Kwiatek*[2], *Łukasz Rudziński*[1]
[1]*Institute of Geophysics- Polish Academy of Sciences, Department of Seismology, Kraków, Poland*
[2]*Helmholtz Centre Potsdam- GFZ German Research Centre for Geosciences, Section 4.2: Geomechanics and Scientific Drilling, Potsdam, Germany*

We improved near-realtime processing of seismic data by creating an automated workflow for seismic events detection, location and spectral parameter estimation in a form of a Python package. For detection task we take advantage of EQTransformer - deep neural network picker supported by GaMMA phase association. For source location we use both NonLinLoc (picking/travel-time based algorithm) and BackTrackBB software (partial waveform stacking algorithm). The source parameters including seismic moment, source size, static stress drop, apparent stress and radiation efficiency are calculated using spectral fitting method, where the inverse problem is solved using Markov-Chain Monte-Carlo method. Package performance was tested on the data from the LUMINEOS local surface network composed of 24 sensors located in Legnica-Głogów Copper District (LGCD), Poland. The region is one of the most seismically active in Europe, with several thousand seismic events induced every year (M>0.4) by copper ore mining and maximum local magnitudes reaching M4.2.

We used our workflow to analyze the seismicity framing strong mining rockburst in the LGCD on November 29, 2016. This tragic M3.4 event caused 8 fatalities and massive tunnels collapse. We aim to recognize plausible spatio-temporal changes of the source parameters revealing the source contribution to the damaging potential of this induced earthquake sequence. The obtained results can be used not only for scientists but also mining engineers, who are responsible for safety in the mine.

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S04c - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Application of seismic data to non-earthquake studies: thunder-source inversion and realtime economic growth estimation

DOI: 10.57757/IUGG23-3745 - LINK

Tae-Kyung Hong[1], Seongjun Park[1], Junhyung Lee[1], Jeongin Lee[1], Byeongwoo Kim[1]
[1]Yonsei University, Earth System Sciences, Seoul, Korea Republic of

Seismic stations are operated 24 hours, recording groundmotions by various non-earthquake sources continuously.Meteorological phenomena and human activities areexamples of non-earthquakes. The rapid air expansion bylightning produces a shockwave that creates a cracksound, thunder. Thunder-induced seismic waves recorded atdense seismic stations in Seoul, South Korea are analysedfor inversion of thunder source spectra. Thethunder-induced seismic signals were well identified atdistances of < ~20 km. In the course of source-spectralinversion, the propagation and acoustic-to-seismiccoupling effects are counted. Direct acoustic-to-seismiccoupled seismic waves present apparent phase velocitiesof sound speed in atmosphere. Thunder-induced seismicwaves are dominant at high frequencies (>20 Hz). Thethunder-induced acoustic waves in the atmosphere areobtained by removing the acoustic-to-seismic couplingeffect and site-response effect from the observedthunder-induced seismic waves. The quality factors foracoustic wave attenuation in the atmosphere aredetermined. We determine acoustic thunder source spectraare determined by stacking the inverted acoustic spectra.Human activity is another major source of high-frequencyseismic noise. Analysis with seismic noises in threeconsecutive months of each year enables us to estimatethe noise levels without seasonal effects. The daytimeseismic noise-level changes in major cities of 11countries are assessed using the 3 month records fordecades. The annual seismic noise levels present strongcorrelations with gross domestic product (GDP),particularly with manufacturing and industrial GDP. Theseismic noise levels increase quickly with GDP in low GDPregions but slowly in high-GDP regions. The seismic noiselevels increased by 14 % to 111 % for 5-23 yr dependingon the economic conditions. The high-frequency noiselevel may be a proxy to present the economic condition.

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S04c - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Towards Routine Automatic Estimation of Standard Body- and Surface-Wave Magnitudes at ISC

DOI: 10.57757/IUGG23-1893 - LINK

Natalia Poiata[1], *Domenico Di Giacomo*[1]
[1]*International Seismological Centre, International Seismological Centre, Thatcham, United Kingdom*

Magnitude is a fundamental source parameter facilitating the characterisation of the size and amount of energy released by earthquakes and other types of seismic events. It provides an important input to a wide variety of seismological studies, from seismic hazard to statistical analysis of seismicity and nuclear explosion discrimination. Seismic network operators and observatories routinely estimate standard types of body- and surface-wave magnitudes using established procedures, however, the reported results are often inconsistent due to the differences in the implemented waveform processing schemes. These inconsistencies become more evident with the increasing volumes of recorded data currently faced by seismic networks. With the scope to address the issue, the International Seismological Centre (ISC; www.isc.ac.uk) aims to provide a routine estimation of the standard body- and surface-wave magnitudes using the global waveform data. We take the advantage of the comprehensive event-related information at ISC and the increasing amount of openly available, from the seismological data management centres, waveform data to provide an automatic and reproducible estimation of standard magnitudes following the guidelines of the International Association of Seismology and Physics of the Earth's Interior (IASPEI) Working Group on Magnitude Measurements.

In this presentation we describe the details of the procedure and examine the results of the magnitude estimations for over 69,000 earthquakes (M > 4.0) reported in the ISC Bulletin for 2016-2020. We will further discuss the performance of the procedure, compare obtained estimated magnitudes with those in the ISC Bulletin and present the advantage of including broadband body- and surface-wave magnitudes.

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S04c - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Automatic event detection with back projected method: Example of Taiwan seismic network

DOI: 10.57757/IUGG23-3177 - LINK

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[1]*Academia Sinica, Institute of Earth Sciences, Taipei, Taiwan Province of China*
[2]*Central Weather Bureau, Seismological Center, Taipei, Taiwan Province of China*

Automatic earthquake monitoring is widely used by a seismic network and fast reported for significant events. Traditional earthquake location methods require P-wave and S-wave manual phase picking or accurate automatically obtained first arrivals as first step. The event location is determined based on the inversion to best fit of all travel times. In this study, we design a procedure to locate earthquakes based on back-projection stacking of seismic energy. The stacking of seismograms using a varying time delay computation based on a regional crustal model. The grid search is used to fine optimum location in 3-D spatial grids based on the maximal value of all stacked seismograms after tested all grids of the model. Synthetic test indicated the stable results to find collect location and original time. Taiwan is one of the most seismically active regions in the world. The seismic networks of CWBSN, TSMIP and BATS are designed for different purposes to record seismic ground motion in Taiwan. Almost those real-time data streams are continuously transmitted back to Academia Sinica. We have tested event location based the catalog of the CWB fast report using this dataset. The real data testing got high consistent results of event within network and moderate consistency for event located in the border of network. Our determination procedure is under polishing to get stable results and speed the process time. It provides a potential application to join the system of earthquake warning system in Taiwan and other seismic tectonic applications in the near further.

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S04c - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Detection of hidden earthquakes after the 2011 Mw9.0 Tohoku earthquake and their relation to regional crustal deformation

DOI: 10.57757/IUGG23-0631 - LINK

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Seismic activity increased throughout Japan after the 2011 Mw9.0 Tohoku earthquake. Microearthquakes (M<2 inland and M<3 offshore) were not adequately catalogued, making it difficult to comprehensively quantify changes in seismic activity after the 2011 Tohoku earthquake. Therefore, we developed an automatic source determination method using machine learning and detected "hidden" earthquakes that were more than twice as large as those in the conventional earthquake catalog from March 2011 to February 2012. This method includes phase discrimination using CNN and quality control using ensemble learning. We then merged the automatically determined catalog with the JMA unified earthquake catalog, and extracted inland seismic activity throughout Japan from the newly obtained merged catalog. We quantified the seismic activity based on the ETAS model from the obtained seismic catalog. The relative change in background seismic activity in April 2011 indicates that it is, on average, two to three times higher than before the Tohoku earthquake. We also found a positive correlation between the background seismic activity ratio and the maximum shear strain rate in the vicinity, based on the one-month difference in GNSS data. The obtained hidden earthquakes contribute to better resolution and quantification of seismic activity.

Acknowledgements
We used the waveforms from JMA, NIED, universities, and institutions, and the JMA unified earthquake catalog. We used GEONET (F5) coordinate data from GSI. We used Kasahara et al. (2016) to estimate ETAS parameters, and Shen et al. (1996, 2015) to calculate strain rates.

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S04d - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Using relative event locations of swarms of small earthquakes to look for seismically active structures in Northeastern North America

DOI: 10.57757/IUGG23-0347 - LINK

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Swarms of small earthquakes and microearthquakes have been observed in several different places in the northeastern U.S. and southeastern Canada over the past several decades. The modern seismic network that has operated during this time has allowed earthquakes to magnitudes below M 1.0 in these swarms to be detected and located. A relative earthquake location method using waveform crosscorrelations allows for very precise relative event locations to be computed, which can be used to look for spatial trends in the earthquake swarms. Absolute events locations are best determined using event recordings on portable seismic instruments in the epicentral area. Relative and absolute location analyses of several swarms show a consistent pattern of the swarm seismicity aligning along known or suspected preexisting faults. These swarms, located in New York, Connecticut, Maine and New Brunswick, may be indicating which pre-existing structures in Northeastern North America might be seismically active in the future. Whether or not these structures could host a strong earthquake in the future is not clear from the data. Even so, the analyses suggest that studies of the relative event locations of future swarms of small earthquakes and microearthquakes may help clarify the picture of which pre-existing zones of weakness may pose the greatest seismic hazard in the region.

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Study of waveform envelope method in foreshock identification

DOI: 10.57757/IUGG23-3137 - LINK

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The *M*6.4 Yangbi earthquake, which occurred in Yunnan Province on May 21, 2021, has attracted a lot of attention for its abundant foreshocks and superior monitoring capability around the mainshock. It seems to be a typical foreshock-mainshock-aftershock sequence in China Mainland in recent decades, and the key question is whether it is possible to distinguish foreshocks from normal seismic activities. The *b*-value derived from the Gutenberg-Richter (GR) law, as an important seismicity parameter, has the characteristics of decreasing during foreshock activity and increasing during normal aftershock sequence by previous studies. At present, the sequence's *b*-value is usually calculated by using the earthquake catalog, which makes it difficult to obtain the *b*-value results in a short time after the earthquake. In this study, we select the foreshock event waveform recorded by the station closest to the earthquake epicenter and obtain the envelope function of the waveform. Each peak of the envelope can be regarded as an earthquake event. The peak amplitude and time correspond to the magnitude and time of earthquakes. Similar to the GR relationship, the corresponding relationship between magnitude and peak number is preliminarily established, and the corresponding *b*-value results are obtained. This study aims to explore the effectiveness of the waveform envelope method to identify foreshocks in China mainland, and tries to solve the problem that the *b*-value cannot be accurately calculated due to the lack of catalog after a large earthquake.

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Modeling and analysis of Distributed Acoustic Sensing (DAS) data in Geothermal environments

DOI: 10.57757/IUGG23-1656 - LINK

Davide Pecci[1], Juan Porras[2], Michele De Solda[2], Francesco Grigoli[2], Eusebio Stucchi[2], Renato Iannelli[1]
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[2]Università di Pisa, Dipartimento di Scienze della Terra, Pisa, Italy

DAS technology is particularly suitable for microseismic monitoring application in geothermal environments, especially for the development of Enhanced Geothermal Systems. This acquisition technology still lacks appropriate modeling and analysis tools able to handle such a large amount of data without losing efficiency. Since free DAS datasets are still a rarity, we aim to generate an open-access synthetic (but realistic) DAS dataset that may help the geophysical community to develop “ad hoc” data analysis methods suitable for these datasets. In the presented work we make use of the software 'Salvus' which allows the simulation of DAS data. In particular, it outputs a strain measurement between all points defined as receivers in the simulation. Using the repositories of DAS data collected at the geothermal test site FORGE, in Utah (USA), we tried to simulate realistic DAS acquisition conditions of seismic events related to low-magnitude natural seismic activity from the nearby Mineral Mountains and microseismic events related to hydraulic stimulation operations for the generation of an EGS. In order to obtain realistic synthetic data, we first analyze the spectral properties of real noise waveforms by using the Power Spectral Density Analysis. We model the synthetic noise waveforms using a stochastic approach. Then we add it to the synthetic event traces and compare them with the observed ones. We finally test a new semblance-based event detector on a 1-hour continuous waveforms of synthetic data to evaluate the performance of the detector in different operational conditions (e.g., different noise levels and inter-event times).

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S04d - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Near real-time waveform-based methods for detection and location of microseismicity using DAS

DOI: 10.57757/IUGG23-2919 - LINK

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[1]*University of Bochum, Institute of Geology- Mineralogy and Geophysics, Bochum, Germany*
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Recent work has shown increasing utility of Distributed Acoustic Sensing (DAS) in microseismic monitoring operations, including those related to Enhanced Geothermal Systems. DAS can transform km-long fiber optic cables into a distributed array of seismic sensors capable of imaging the entire wavefield. However, the large quantity of data DAS acquisition produces hurdles to near-real-time seismological data analysis. In this study, we test waveform-coherence-based methods used to detect and locate microseismic events with DAS data that can be applied in near-real time. The merits of the approach rest in its potential to enable continuous seismic monitoring using DAS.

The detection approach uses a semblance-based method that evaluates waveform coherence along hypoerbolic trajectories with different curvatures and vertex positions. It returns a time series of coherence values that enable the declaration a seismic event when coherence values exceed a given threshold. We then test a waveform-stacking method based on the use of trace short-term-average/long-term-average (STA/LTA) values to estimate event hypocenter locations. We stack waveforms based on theoretical travel times for both P- and S-phases and constrain the source location based on peak stacked amplitude values. A grid search of variable source locations and origin times produces the best-fit solution where the stacked amplitudes reach peak values. The method does not require phase identification and picking and can be applied to low signal-to-noise-ratio data. We will present results of the method using synthetic data and validation on real data from the 2022 FORGE (Utah, USA) DAS dataset.

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S05a - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

SeaFOAM: a Year Long DAS Deployment in Monterey Bay, California

DOI: 10.57757/IUGG23-3611 - LINK

Barbara Romanowicz[1], *Yuancong Gou*[1], *Li-Wei Chen*[1], *Richard Allen*[1], *Julien Marty*[1]
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Distributed Acoustic Sensing (DAS) is being explored in a variety of environments as a promising technology for the recording of seismic signals in dense array configurations. There is a particular interest for deploying DAS arrays on the ocean floor, as this environment presents formidable challenges for conventional seismology. Recent DAS studies on submarine cables demonstrate promising data fidelity showing detections of local and teleseismic events, as well as microseisms, infragravity waves and other oceanic signals spanning a broad frequency range. However, most of such experiments are short-term (lasting a few days to a few weeks) and lack systematic assessment of the instrument response, background noise and its seasonal variations, and, more generally, instrument capability. Here, we describe first results from a longer term (1 year starting in July 2022) DAS experiment on the Monterey Bay Accelerated Research System (MARS) cable in Monterey Bay (California), which extends offshore for a length of 52 km, and on which we have been acquiring data since July 2022, for almost a year. Here we describe the experiment and present examples of observations background noise and a variety of detected signals, including microseisms, infragravity waves, regional and teleseismic earthquakes (in particular T-waves) over the first 10 months of the deployment. In addition to these observations, one of our goals is to integrate the continuous DAS data into the real-time seismic monitoring system in northern California including Earthquake Early Warning.

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S05a - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Distributed Acoustic Sensing in the Puget Sound and Puget Lowlands, Washington, USA

DOI: 10.57757/IUGG23-5012 - LINK

Bradley Lipovsky[1], Veronica Elgueta[1], Yiyu Ni[1], Marine Denolle[1], Dale Winebrenner[2], Holberg Leo[3], Mark Zumberge[4]
[1]University of Washington, Department of Earth and Space Sciences, Seattle, USA
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The recent democratization of optical fiber geophysics opens new inroads to explore complex and difficult-to-access wave propagation environments. Here, we present an analysis of one year of continuous Distributed Acoustic Sensing (DAS) data recorded along two optical fiber cables located in the Puget Sound and Puget Lowlands, Washington, USA. The first cable is 12 km long and includes a 4 km long subsea component (average ~100 m water depth) and the second cable is 30 km long in an urban to suburban setting. Both DAS deployments make use of a Sintela Onyx interrogator. During the observation time, interrogators on both fibers observe local, regional, and teleseismic earthquakes. We find that the overall detection threshold for our terrestrial DAS observations is equal to and in some cases slightly better than the urban seismometers of the Pacific Northwest Seismic Network (PNSN). In addition to DAS, we present concurrent Ultrastable Laser Interferometry (ULI) observations on fiber in the same cable as one used for DAS. Distant teleseismic earthquakes provide a means to compare DAS and ULI strain measurements and yield strain correlation coefficients greater than .95. Regional earthquakes generate subsea Scholte waves and thereby enable a lower detection threshold than PNSN stations. A fiber running through the city of Seattle is used to map the spatial variability of engineering site parameters such as VS30. These results point the way to several areas of progress in understanding earthquake hazard including using optical fiber geophysics.

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S05a - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Towards continuous monitoring in the oceans with submarine telecommunications cables using fibre optic technique: the SUBMERSE project

DOI: 10.57757/IUGG23-1678 - LINK

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Seismology Section Helmholtz Center Potsdam, Potsdam, Germany

In last few years, a number of technologies to use fibre optic cables as sensing devices have been established, among them Distributed Acoustic Sensing (DAS) and State-of-Polarisation (SoP). The potential of these technologies for monitoring a range of Earth System parameters in submarine cables has been demonstrated through several pilot experiments. Yet, continuous access to sub-marine optical fibre scientific data has currently not been achieved anywhere, neither has full integration of the various techniques.

The SUBMERSE project links Research and Education Networks (NRENs), universities, research institutes and industry to establish multi-method monitoring along submarine optical telecommunication cables at several key cable routes branching off from Portugal, Madeira, Svalbard and in the Aegean. Those pilot sites should serve as a blueprint for establishing continuous monitoring services along many more cables.

The project comprises technical developments for integrating DAS and SoP measurements, for establishing differential SoP measurements between repeaters and for operating DAS in 'lit' fibres, i.e., fibres carrying telecommunications traffic. Furthermore, a range of geoscientific and marine biology use cases are included, which seek to establish code/services for monitoring earthquakes, tracking whales, measuring the sea state and other Earth System variables. Effective data management, dissemination and training through community specific services will be addressed in several tasks as they are crucial for the success of this project due to the large size of data, sensitivity of a subset of the recordings and current lack of established community standards. SUBMERSE clearly commits to open and FAIR data exchange.

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S05a - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Detecting earthquakes and underwater controlled explosions using distributed acoustic sensing on submarine cable infrastructure

DOI: 10.57757/IUGG23-2739 - LINK

Alan Baird[1], Jan Petter Morten[2], Volker Oye[3]
[1]NORSAR, Solutions, Kjeller, Norway
[2]Alcatel Submarine Networks Norway, Signal Processing, Trondheim, Norway
[3]NORSAR, Applied Seismology, Kjeller, Norway

Distributed acoustic sensing (DAS) can be deployed on existing submarine fibre optic cables to add sensor capability to the cable infrastructure. This does not require offshore installations and the DAS interrogation can also coexist with data traffic on telecom fibres. In this way, DAS provides a cost-efficient means to monitor marine cables with application to environment studies and seismology, seabed activity from e.g. fishing, and changes to the cable condition. For monitoring of seismic signals, DAS provides several advantages over traditional seismic sensors including a dense spatial sampling of the wavefield (on the order of metres) over long ranges (>100 km). It also poses some challenges. For example, the single-component measurement (along the cable) can lead to ambiguity in event location due to the unresolved directionality of incoming waves.

Here we will present observations from a long-term study on a Tampnet North Sea submarine telecom cable. We have characterized local earthquakes and underwater explosions in addition to anthropogenic activity. After post-processing to suppress marine noise, a detailed image of the earthquake wavefield with clear P- and S-arrivals can be observed. Recordings of underwater explosions are characterized by low-frequency first arrivals refracted through the subsurface followed by slower propagating high frequency and high amplitude direct arrivals through the water column, which can clearly be observed over the full length of the cable. Furthermore, tracking the travel-time moveout along the non-straight cable route allows for positioning of the source, which we demonstrate by back-propagating the recorded wavefield.

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S05a - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Overview of the global DAS monitoring month 2023

DOI: 10.57757/IUGG23-2322 - LINK

Andreas Wuestefeld[1]
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The IRIS DAS RCN has coordinated a global measurement campaign of fibre optic sensing systems. The campaign took place between 1 Feb – 28 Feb 2023 and comprises triggered DAS data from teleseismic events (>M5, USGS catalogue) with contributions from academia and industry (downhole, pipeline, railroads, etc.). The dataset comprises more than 20 DAS systems recording at the same time in different regions of the globe with cable length between 1 and 100km. The nominal recording parameters are 100Hz and 10m channel spacing, but varies between systems. The recorded data will help in establishing the next-generation global monitoring system based on DAS. About 150 interesting global earthquakes are covered during that period, and each participant upload triggered data window of 3600 to a central storage location. This thus also helped to identify bottle-necks in data format, storage, and legal issues. in addition to the triggered event data, continuous data for 24 hours of 14-02-2023 are available for many systems. We anticpate lively and interesting research to be possible with such a rich and unique dataset.

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S05a - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Seismic and environmental observations from a North Atlantic seafloor sensor array created from a trans-oceanic submarine cable

DOI: 10.57757/IUGG23-4366 - LINK

Giuseppe Marra[1], David Fairweather[2], Valey Kamalov[3], Paul Gaynor[1], Mattia Cantono[3], Sean Mulholland[1], Brian Baptie[4], Jorge Castellanos[3], Georgios Vagenas[1], Jacques-Olivier Gaudron[1], Jochen Kronjäger[1], Ian Hill[1], Marco Schioppo[1], Irene Barbeito Edreira[1], Kathryn Burrows[1], Cecilia Clivati[5], Davide Calonico[5], Andrew Curtis[2]
[1]National Physical Laboratory, Time and Frequency, London, United Kingdom
[2]University of Edinburgh, Grant Institute- School of Geoscience, Edinburgh, United Kingdom
[3]Google LLC, Google, Mountain View, USA
[4]British Geological Survey, Earthquake Seismology, Edinburgh, United Kingdom
[5]Istituto Nazionale di Ricerca Metrologica, QN Metrologia quantistica e nanotecnologie, Torino, Italy

Optical interferometry can be used to measure the propagation time of the light along fibre optic cables, enabling the detection of environmental perturbations such as earthquake waves as they interact with the fibre [Marra et al., 2018]. However, at any point in time, the measured signal is an integration of the optical path length changes along the entire fibre. This can result in a high measurement noise floor since the ambient noise along the entire length of the seafloor cable is integrated. Over the lengths of thousands of kilometres of transoceanic seafloor cables, this can prevent the detection of smaller magnitude events.

We present a novel technique that allows many discrete spans along a single fibre optic cable to be used as individual ocean bottom seismometers. These spans are tens of kilometres long and this reduction in length of each line-receiver allows us to monitor specific locations along the cable path. From an observation window of four months, we show that earthquakes, tides, wave heights and ocean microseisms can all be recorded on individual spans between repeaters on a 5,860 km-long transatlantic cable, in addition to monitoring along the whole cable length.

On the continental shelf we observe strong correlations between periodic signals at different frequencies with tides, wave heights and microseisms. In the comparatively quieter deep ocean we have detected two teleseismic earthquakes greater than M_w7. Other enigmatic signals related to ocean tides and the solid Earth's microseisms are also evident.

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S05b - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

The joint project SENSE – fibre-optic strain sensing with respect to a known reference

DOI: 10.57757/IUGG23-5037 - LINK

Charlotte Krawczyk[1,2], Christopher Wollin[1], Ehsaninezhad Leila[1,2], Sascha Liehr[3], Andre Kloth[3], Julia Kirchner[3], Max Hahn[3], Martin Lipus[1], Johannes Hart[1,2], Mohammadmasoud Zabihi[4], Katerina Krebber[4], Konstantin Hicke[4], Bernd Weber[5], Thomas Reinsch[6]

[1]GFZ German Research Centre for Geosciences- Potsdam- Germany, Geophysics, Potsdam, Germany
[2]Institute for Applied Geosciences- TU Berlin- Berlin- Germany, Planning Building Environment, Berlin, Germany
[3]DiGOS Potsdam GmbH- Potsdam- Germany, Research and Development, Potsdam, Germany
[4]Bundesanstalt für Materialforschung und -prüfung- Berlin- Germany, Faseroptische Sensorik, Berlin, Germany
[5]gempa GmbH- Potsdam- Germany, Research and Development, Potsdam, Germany
[6]IEG Fraunhofer- Bochum- Germany, Geotechnologies, Bochum, Germany

For the efficient use of geothermal energy, especially for heat provision, energy must be provided close to a consumer structure, thus in urban areas. Exploration for potential reservoir or storage horizons and their microseismic monitoring during operation are, therefore, mandatory.

For this purpose, the joint project SENSE tests seismic exploration and monitoring approaches based on fibre-optic sensing in urban areas using both active and passive seismic sources. To carry out the seismic measurements, a field-ready demonstrator is being built to carry out spatially distributed dynamic fibre-optic strain measurements. In addition to available instrumentation, strain changes with respect to a known reference are recorded, thereby also enabling the detection of long-term/quasi-static strain changes. This brings decisive advantages with regard to the detection of deep or long-wave signals as well as for the exclusion of very slow deformation movements in connection with the use of the geological subsurface.

We exemplify the monitoring of borehole operations and the horizontal recording of the seismic wave field using cables in Berlin and Potsdam with the new developments tested. Processing workflows encompass shot gather extraction, and picking of dispersion curves that yield after inversion shear wave velocity models exposing several velocity interfaces. To this end, we expect that SENSE will deliver new options for urban monitoring also beyond geothermal.

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S05b - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Towards probing the urban subsurface using Distributed Acoustic Sensing (DAS) deployed on dark fiber

DOI: 10.57757/IUGG23-4539 - LINK

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Characterizing and monitoring the highly variable near-surface underneath urban areas is crucial for understanding phenomena such as resource distribution and storage potential, changes in hydrological systems, and seismic hazard at the sub-kilometer scale. Our current understanding of the urban subsurface is limited by our ability to image its structure and temporal variations at high resolution using classical geophysical approaches. Distributed Acoustic Sensing (DAS) deployed on unused telecommunication fiber-optic cables (dark fibers) is an attractive alternative to classic seismological studies in urban areas, as it enables continuous recording of the seismic wavefield across long distances (10's of km) at high spatial (~1 m) and temporal (down to seconds) resolution across a broad frequency range (mHz to kHz).

Here, we explore the potential and challenges of using DAS deployed on dark fiber networks for characterizing and monitoring the near-surface beneath urban areas. We will discuss dark fiber experiments conducted in a variety of settings, including several km-long profiles crossing agricultural areas and densely populated centers in California, and experiments conducted within the city of Potsdam (Germany). We evaluate the usability of anthropogenic signals as passive sources for near-surface imaging and monitoring, as well as the potential for active source seismic imaging in complex noise environments. Challenges associated with poorly documented deployment and coupling conditions of dark fiber networks and the large data volumes generated in these studies will also be discussed. Ultimately, we aim at providing insights into the challenges and opportunities of using dark fiber DAS for understanding the urban subsurface.

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S05b - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Passive Imaging of Shallow Subsurface in Urban Melbourne Using Distributed Acoustic Sensing

DOI: 10.57757/IUGG23-3152 - LINK

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Distributed Acoustic Sensing (DAS) provides a new, non-invasive means for high resolution subsurface imaging in urban environments by repurposing existing telecommunication cables. However, urban fibre optic networks, which are designed around telecommunication needs, introduce unique challenges to passive seismic imaging including complicated array geometry and non-uniform seismic noise. A 25-km long DAS array was deployed along a telecommunication fibre that spans across metropolitan Melbourne, Australia for a duration of 3 months (December 2021 to March 2022). This dataset provides an ideal test case to address the challenges of using urban dark fibre and establish an effective workflow for ambient noise correlation with DAS recordings in urban settings. Traffic noise from vehicles and trains are the dominant signal at a frequency range of 1-30 Hz. Ambient noise correlation is performed using NoisePy, a high-performance python tool specifically designed to deal with large data volume. Cross-correlation functions show clear surface wave dispersion up to 15 Hz. Acausal move-out times are also observed, indicating strong scatterers off the fibre array and varying ground-coupling conditions. The subsurface velocity model obtained from ambient noise correlation reveals strong structural variations at 10-m scale up to 1 km depth across Melbourne and shows good correspondence with the mapped geological boundaries including an 800 kyr basalt flow and Miocene marine and terrestrial sediments. The exciting results from the Melbourne experiment demonstrate that DAS can be used to build high-resolution subsurface models for metropolitan areas with high seismic hazard risk that may be poorly instrumented with inertial seismometers.

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S05b - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Dark fiber for rapid aftershock response: Capturing the 2022 M6.4 Ferndale sequence in northern California, USA

DOI: 10.57757/IUGG23-0607 - [LINK]

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[7]California Geological Survey, Geology, Arcata, USA

Three days after the 2022/12/20 M6.4 earthquake near the Mendocino triple junction, we deployed a distributed acoustic sensing (DAS) system on ~15 km of dark telecommunications fiber within 50 km of the mainshock epicenter, sampling at 250 Hz every 2 m, and applied a a real-time automated earthquake detection system.

The detection algorithm estimates coherent array energy and adapts to environmental noise levels; spatial filtering suppresses environmental noise and emphasizes local earthquake signatures. With this system we identified ~5 times the number of earthquakes as in a comprehensive regional catalog (with M_c ~1.9), up to M5.4 (the largest aftershock), and detections are consistent with an independent deep-learning-enhanced catalog based on seismometer data alone. On-site computing provides rapid processing and real-time notification: average latencies for processing 1-second-long time windows with 50% overlap were <0.6 seconds.

Additionally, we deployed nodal seismometers every ~350 m along the DAS array to constrain local ground motions and site conditions. Amplitudes vary strongly along the cable due to a combination of wavefield and site effects, but vary systematically for both P and S waves, and waveform clipping is not observed. Thus, we developed linear site corrections and calculate local earthquake magnitudes DAS strains. In general, the magnitude accuracies are comparable to regional network estimates, and we are evaluating the ability of these DAS data to accurately recover apparent source time functions from empirical Green’s function deconvolutions.

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S05b - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Aftershock monitoring and subsurface imaging with DAS array for the 2022 Menyuan Ms6.9 earthquake, China

DOI: 10.57757/IUGG23-3699 - LINK

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An Ms6.9 earthquake occurred in Menyuan, Qinghai, China on Jan 7th, 2022. This earthquake destructed the high-speed railway passing through the epicentral area and rise concerns on the seismic hazard of the Tianzhu Seismic gap, which is about 150 km long. Two DAS arrays were deployed with about 40km long dark fiber optic cable for aftershock monitoring and subsurface imaging. Three automatic methods were utilized to scan earthquake signals on the continuous data including: a neural network, template-matching method, and a hybrid method integrating array-detection and template-matching. All of three methods reported more than 80% aftershocks in the routine catalog and up to 50% newly detected events. For the template-matching method, using aftershocks occurred in the first two-day as templates provides about 91% catalog events and 50% additional events. The other two methods do not depend on the prior information, which means quicker response. The fault-related signal is also observed on the seismic wavefields of earthquakes, which helps to identify blind faults in the Menyuan basin. Ambient noise tomography method was used to construct 2D Vs profile along one cable. Strong lateral variation emerges and faults can be identified on the NCF COG gather. Such high-resolution shallow structure model and earthquake catalog provides additional information of seismic hazard in the Menyuan region.

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Distributed fiber optic sensing observations at Etna volcano, Italy: An integrated vision

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Mount Etna (Sicilia, Italy) is one of the most active volcanoes worldwide, located at the boundary between the African and the Eurasian plates. It is characterized by the occurrence of many phenomena such as lava flows, ash eruptions, earthquakes. Its eastern flank is also characterized by a complex system of active faults, associated with an eastward flank movement, up until the submarine environment. As Etna flanks are densely inhabited areas, we aim at better understanding the link between these phenomena to better assess associated hazards and risks.

Since 2018, we have been measuring several locations with Distributed Fiber Optic Sensing yearly, enabling us to observe strain at meter-scale spatial interval and on a broad frequency range. We show records and present results from selected cables. Close to the summit active craters, we interrogate dedicated cables, and could analyze the ground response in association with explosions and volcanic tremor. In urban areas, we interrogate telecommunication cables and record local earthquakes. In the submarine area, we interrogate a cable which crosses the North Alfeo fault with several different optical techniques. In the southern flank of the volcano, we show volcanic signals from a cable deployed in a borehole. We also demonstrate how simultaneous multi-fiber measurements can help constrain earthquake hypocenter location.

We discuss opportunities and challenges of using fiber optic cable in various environments such as the Etna volcano and beyond, for an integrated vision from deep processes, their interaction with the sub-surface dynamics and the volcano-tectonic structures.

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S05c - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Linking Distributed and Integrated Fiber-Optic Deformation Sensing

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[3]National and Kapodistrian University of Athens,
Department of Informatics and Telecommunications, Athens, Greece
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Distributed Acoustic Sensing (DAS) has become a popular method of observing seismic wavefields: backscattered pulses of light reveal deformation with meter-scale resolution along a fiber-optic cable. In contrast, a few newer systems transmit light through a cable and collect integrated phase delays over the entire cable, such as the Microwave Frequency Fiber Interferometer (MFFI). The outstanding advantage of these integrated systems is that they can be interrogated over significantly longer distances of hundreds or thousands of kilometers, may be used at the same time as live telecommunication, and can be significantly cheaper. However, they provide only a single time series representing strain over the entire length of fiber.

In the first part of this contribution, we present a theory for integrated fiber optic sensing. This enables a quantitative comparison of these new systems with established DAS measurements. Furthermore, we note that sensitivity to deformation depends critically on local fiber curvature, which offers opportunities to mimic distributed measurements with integrated systems. In the second part, we present the first results of a quantitative, head-to-head comparison of a DAS and the integrated MFFI system using pre-existing telecommunication fibers in Athens, Greece.

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S05c - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Microseismic event detection in continuous DAS data using a convolutional neural network (CNN)

DOI: 10.57757/IUGG23-1820 - LINK

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Detection and localization of microseismicity is an inevitable task to monitor fluid injections into subsurface rocks during hydraulic stimulations. Traditionally, such observations are done with downhole geophones, but in the last years, the usage of distributed acoustic sensing (DAS) using fiber-optic cables placed into boreholes has become a standard technique. However, DAS registrations still have lower signal-to-noise ratios than geophones, i.e., they are not able to detect small-magnitude events. In this work, we develop a convolutional neural network (CNN) that is capable to detect and distinguish P- and S-arrivals in continuous DAS recordings. This network is trained on several hours of DAS data recorded at the Utah FORGE EGS project in 2019. By also incorporating arrival-time information from geophones placed in the same borehole during the training, we are able to shift the detection threshold towards smaller magnitude events significantly. Although the number of microseismic events (≈150) used for training is small, the tested network performance is high and provides a complete event catalog down to magnitude Mw=-1.6. This means, that after a short training phase, the network can be used for long-term real-time observation. Although the network currently only detects seismicity, event localization is feasible with small network adaptations. Furthermore, the methodology and network architecture can be easily adjusted for similar case studies, where long-term seismic monitoring is required (e.g. EGS or CO_2 sequestration).

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S05c - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Real-time detection and analysis of earthquakes with Distributed Acoustic Sensing

DOI: 10.57757/IUGG23-4086 - LINK

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Distributed Acoustic Sensing (DAS) interrogators have become commercially available, enabling long term measurements in diverse environments. Collection of permanent data is facilitating new applications such as earthquake detection.

Pre-installed standard communication fibres can be used for the detection of seismic activities. However, the signal to noise ratio (SNR) is rather low at earthquake frequencies and therefore it is difficult to detect seismic waves at high ambient noise. Although standardized laboratory tests reveal a higher noise floor at low frequencies for DAS interrogators, the detection of earthquakes is still possible through filtering and signal enhancement methods. Furthermore, efficient real-time data evaluation is necessary for early-warning mechanisms.

This article compares data of 3 different fibre lines with different characteristics and ambient noise for earthquake detection. Tests are performed with an inner-city line, which is exposed to high noise by day due to traffic loads and low noise at night. Additionally, a fibre line in a rural area with lower noise behaviour is investigated. Furthermore, DAS measurements at a fibre line at the national underground seismic observatory were performed and compared with the close by seismometers.

In this paper we focus on methods for detection and evaluation of seismic waves and discuss the technical challenges of detecting small signals in big data. The paper also addresses matters of performance related to real-time data evaluation.

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Modelling of DAS cable and ground coupling response using Discrete Particle Schemes

DOI: 10.57757/IUGG23-3287 - LINK

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In the past decade, the use of fiber optic cables to sense ground motion (Distributed Acoustic Sensing-DAS) has become a topic of great interest in seismology because of its wide sensitivity range, dense spatial sampling and new deployment possibilities.

How exactly DAS cables respond to ground motion is however largely unknown, limiting the application of a number of staple seismological techniques (e.g. earthquake magnitude estimation, waveform tomography) that can require accurate knowledge of a signal's amplitude and frequency content.

Here we present a method for accurately simulating a DAS cable and its response. The scheme is based on particle-based numerical modelling, allowing the investigation of the effect of varying DAS-ground coupling scenarios. After computing the strain field directly, we define a virtual DAS cable, formed by a single string of interconnected particles. This allows us to control all aspects of the cable-ground coupling and their properties at an effective granular level through changing the bond strengths and bond types for both the cable and the surrounding medium. Arbitrary cable geometries and heterogeneous materials can be accommodated at the desired scale of investigation.

We observe that at the meter scale, realistic DAS materials, cable-ground coupling and the presence of unconsolidated trench materials around it dramatically affect wave propagation, with differences exceeding at times the magnitude of the recorded signal. These differences show that cable coupling and local site effects have to be considered when designing a DAS deployment and analysing its data when either true or along-cable relative amplitudes are considered.

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S05c - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Strong-motion on DAS: Insights from the 2022 MW 6.9 Chishang earthquake (Southern Taiwan)

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Distributed acoustic sensing (DAS) sees increased utilization in the seismological community in recent years and various applications are investigated for the usage of DAS in different branches of seismology.

Strong-motion seismology uses records of earthquakes of engineering concern (MW>4.5) with hypocentral distances within few hundreds of kilometers. This demands dense networks over a wide area and installation of typical strong-motion instruments (accelerometers) can be achieved quickly and at a reasonable budget, compared to other network types. For DAS, installation and operation are more involved, and deployment is very still limited. Consequently, DAS recordings of nearby large events are still very unlikely and rare compared to accelerometers.

On September 18, 2022, a shallow earthquake sequence with a M_W 6.9 mainshock struck near Chishang (Taiwan) and was recorded by DAS in Hualien city, appr. 100 km north. Shaking of the mainshock and several aftershocks were noticeable in Hualien, though not damaging with PGA recorded at 0.28 m/s^2 nearby the DAS site. The DAS campaign was originally conceptualized as a test suite with different fiber installations: including buried, within a gutter (as in commercial fiber installation) and loose within a basement. The test site is in an urban area affected by surface rupturing during the 2018 Hualien earthquake.

The presented recordings provide not only an unprecedented insight how strong-motion appears on DAS but also how effective different installation techniques are for this kind of event. The waveforms are also compared to records of a collocated broadband seismometer and an accelerometer 1 km away.

Distributed acoustic sensing (DAS) sees increased utilization in the seismological community in recent years and various applications are investigated for the usage of DAS in different branches of seismology.

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S05c - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Understanding non-linear ground response from volcanic explosions and Distributed Dynamic Strain Sensing (DDSS) parameters: An example from Mt. Etna, Italy.

DOI: 10.57757/IUGG23-4924 - LINK

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Distributed Dynamic Strain Sensing (DDSS), a.k.a. Distributed Acoustic Sensing (DAS), is becoming a popular tool for volcano monitoring. The sensing method relies on measuring the phase-shift of Rayleigh back-scattered light throughout the fibre due to strain variations in the fibre glass. This provides distributed strain-rate measurements at fine temporal and spatial sampling intervals. During 3 months in 2019, we recorded signals from thousands of mild volcanic explosions from Mt. Etna using a multi-instrument network deployed in an area at ca. 2.5 km distance from the active craters. Infrasound sensors were laying at the surface with a dense array of broadband seismometers (BB). Two types of fibres were also buried ca. 30 cm depth in the non-consolidated scoria from the area. First fibre was a 1.5 km long standard fibre, interrogated with an iDAS unit. The second fibre was a 0.5 km long engineered fibre, interrogated with a Carina unit. Relation between infrasound and DDSS data suggests a ground response of the loose scoria due to the acoustic pressure waves from explosions. Further analysis suggests a non-linear relationship between acoustic pressure and strain-rate data. However, signal saturation is encounter in some of the strain-rate data, which affects the interpretation of the non-linear relation. Therefore, we present an algorithm to correct the signal artefacts, allowing us to restore the true strain-rate signal and exceed the dynamic range limited by the initial DDSS recording parameters. The outcome includes strategies in the selection of acquisition parameters prior to DDSS campaigns to avoid signal saturation.

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artefacts, allowing us to restore the true strain-rate signal and exceed the dynamic range limited by the initial DDSS recording parameters. The outcome includes strategies in the selection of acquisition parameters prior to DDSS campaigns to avoid signal saturation.

S06a - Pre-Instrumental Earthquake Data

In the wake of a big quake

DOI: 10.57757/IUGG23-1714 - LINK

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The 18th-century European press network functioned in a non-linear way: newspapers tended to publish news from far-off countries rather than those of merely local interest. Thus, some Italian news may be only reported in non-Italian gazettes, or Italian gazettes omit to report some interesting details that reach instead – via the underground network of handwritten reports and diplomatic correspondence – some foreign gazettes. On the other hand, however, exaggerations or outright hoaxes are frequent both in Italian and non-Italian gazettes.

In order to understand how journalistic communication functioned and how the traces of some earthquakes were collected and preserved by seismological compilations, we examined the output of several Italian and European gazettes in the months after the great Lisbon earthquake of 1 November 1755.

During this period the European press network overflows with reports of the effects of the “big one” in Portugal and abroad, and also publish a spate of news of other earthquakes in Europe and the Mediterranean area. Some - the 9 December 1755 Valais earthquake, the 13 February 1756 Rhodos, and the 18 February Düren earthquakes - were real enough and quite strong too. Others were minor or - in some cases - even wholly fictitious events. Our survey discovers the traces of a few earthquakes still unknown to the current parametric catalogues and allows us to reevaluate an earthquake that turns out to represent the historical maximum for the city of Treviso (Veneto, Italy).

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reevaluate an earthquake that turns out to represent the historical maximum for the city of Treviso (Veneto, Italy).

The information background of pre-instrumental seismicity in Europe and possible improvements

DOI: 10.57757/IUGG23-2648 - [LINK]

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The European PreInstrumental Earthquake CAtalogue (EPICA) the 1000-1899 was recently compiled as an input dataset of the European Seismic Hazard Model 2020. EPICA updates, maintaining the same principles and compilation strategy, the SHARE European Earthquake Catalogue (SHEEC) 1000-1899, which was the first continent-wide catalogue resulting from standardised procedures applied to a harmonised set of historical macroseismic data. EPICA exploits the updated knowledge of the European pre-instrumental seismicity gathered in the European Archive of Historical Earthquake Data (AHEAD). These data are macroseismic intensity distributions supplied by descriptive historical seismological studies and online macroseismic databases, and parameters contained in regional catalogues. Among these datasets, the most representative of the knowledge of each earthquake was chosen independently from national constraints and parameterized with standard procedures. As a result, the harmonisation of earthquake data and parameters across country borders is maximised.

However, the availability and reliability of data across Europe is incomplete and uneven, and the level of update of both macroseismic studies and parametric catalogues differs considerably from one area to the other. Such heterogeneity reflects on the uniformity of the catalogue, so that the room for improving the knowledge of the European seismic history is still large. In addition, the methods for the definition of macroseismic parameters and their associated uncertainties remained unchanged in the last decade and need to be improved.

This works aims at highlighting both advantages and unsolved questions related to the knowledge of past European seismicity, focusing on possible improvements.

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S06a - Pre-Instrumental Earthquake Data

Looking for undocumented earthquake effects: an application to Italian localities

DOI: 10.57757/IUGG23-2633 - LINK

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Integrating macroseismic intensity data recorded through time with those calculated from epicentral parameters with intensity prediction equations (IPEs) is an effective way of investigating the knowledge of the seismic history (i.e., the list of documented effects) of a given site and to estimate its representativeness. For this purpose, we calculated the effects that were not documented at a set of sites in Italy by considering an IPE constrained with intensity values documented at close sites for the same events.

We first selected 228 localities according to their geographical distribution and to the number of related documented intensity data contained in the last version of the Italian Macroseismic Database DBMI15 and we then estimated the number of earthquake effects that could be potentially lost. The latter were calculated with a probabilistic approach in order to take into account both the uncertainties related to the assessment of the intensity value at the site and the nature of macroseismic data (ordinal, discrete, and range limited).

We finally provided a quantitative estimate of the effects of known past earthquakes that can be considered potentially lost at the 228 sites analyzing the results at both the local (site-by-site) and regional scale. The results showed that at least one effect with intensity greater than or equal to 6 MCS could be potentially lost with a high probability at almost the totality of the investigated sites. Moreover, some geographical dependences and correlations with the intensity levels were identified.

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Wartime earthquakes in borderlands

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Sofia Baranello[1,2], Romano Camassi[1], Viviana Castelli[1]
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The amount of traces that an earthquake may leave in historical records depends on many variables: its size, the relevance (political, economic, and cultural) of the area affected by it, the historical period in which it occurred, the space/time concomitance of other major geopolitical events that may overshadow the earthquake and hinder the production and circulation of information on its effects. If an earthquake is less than destructive and affects a marginal or border area, the likeliness that its memory will be quickly effaced is particularly high in wartime.

Such an earthquake occurred during the French phase of the Thirty Years' War (first half of the 17th century) in the Duchy of Savoy, an Alpine region and the main Italian theatre of war. It left only vague traces in a few seismological and historical compilations (Italian and European), none of the European parametric catalogues picked it up. The chance discovery of a short description of its effects in a diplomatic dispatch recently led us to undertake its study.

It was no easy feat, given the complexity of the socio-political context of the time, characterized by war events affecting all the territories where this earthquake could have been felt, but the effort was worthwhile because this earthquake currently turns out to be the most significant one in the seismic history of a major industrial city of northern Italy.

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Macroseismic Comparison of the 1867 and 2014 Paliki, Kefalonia earthquakes

DOI: 10.57757/IUGG23-2572 - LINK

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We present the Paliki, Kefalonia, Greece earthquakes of 1867 and 2014 in an effort to compare the effects and assign macroseismic intensities of earthquakes originating from the same seismogenic source. For the first event our sources are the three detailed field reports by Schmidt, Typaldos and Vergotis and four local newspapers. For the 2014 events (26 January and 3 February) the second-degree building inspections and the vulnerability categorization following the 2011 census, as well as ample photographic material and witness reports were used for intensity assignment. In both cases, 90% of the localities on the island were almost similarly affected by both earthquakes. Particularly, the studied earthquakes ruined or severely damaged the villages and towns in Paliki peninsula. We investigate the evolution, in terms of population and building activity, of these localities within the time span of 147 years between the two earthquakes, taking also into account the several significant earthquakes that occurred within this span. A total number of 65 (1867 event) and 97 (2014 events) intensity datapoints are collected from the island of Kefalonia. The macroseismic parameters of the historical event, when compared to the instrumental ones, show significant similarities.

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A quantitative archaeoseismic approach to constrain ground motion features of the 1919 earthquake in Sant'Agata del Mugello (Tuscany, Italy)

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Do we have any idea about the ground motion features associated with a pre-instrumental earthquake?
We propose a protocol based on the idea that historical buildings may record ancient tremors. Their effects may be read from direct traces or deduced from reconstruction phases. The medieval church of Sant'Agata del Mugello (Tuscany, Italy) is used as a case study to illustrate the interdisciplinary approach based on building archaeology, earthquake engineering, and engineering seismology. According to archives, the church was damaged by the 1542 and 1611 earthquakes (Mw 5.8 and Mw 5.1) but resisted the 1919 earthquake (Mw 6.2). Archives data and stratigraphic analysis give the key elements to trace back the state of the building before and after each historical earthquake. The geometrical survey, stratigraphic analysis, and Ambient Vibration Testing allow calibrating of a Finite Element model of the church. An innovative static non-linear analysis provides the elastic limit of key control points to follow the response of the building to the seismic loading. The linear updated model is then used to discriminate ground motion compatible with the observed failure mechanisms of the medieval church. Finally, prospective Intensity Measures such as Peak Ground Acceleration, Arias, Housner Intensity (etc.) of the 1919 earthquake are discussed.

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Damage from small and moderate earthquakes in northern Europe: An exercise in searching for historical documentary sources

DOI: 10.57757/IUGG23-0057 - LINK

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This investigation searches for contemporary written documentation on damaging earthquake consequences in intraplate northern Europe between the late 1800s and early 1900s, when the region experienced a period of elevated seismicity of earthquakes with M < 5.5. Augmenting information is expected to improve the success of intensity assignment and the subsequent determination of non-instrumental magnitude and epicenter. Ultimately, such examples would provide helpful validation of the intensity scale. This is demanding, however, because damage levels in the region can typically be linked to the masonry parts of houses, timber being resilient to ground shaking, and only ordinary buildings are recommended to be used for intensity assessment by the EMS-98 guidelines.
Once the contemporary newspapers have been exhaustively scanned, the search for archived documentation about the non-structural earthquake impact faces several challenges. Many documents were not written in the first place for dwellings that sustained some damage, but were not insured. Documentation lost over the decades is all too familiar. Earlier work on an earthquake of 1898 showed that both direct and indirect earthquake effects occurred: Ground shaking cracked unreinforced masonry chimneys and stoves, which posed a serious fire hazard in predominantly wooden towns. Additional cases from 1882 and 1904 are explored. Indirect earthquake hazards can occur at long epicentral distances, but establishing a time frame for them can be difficult. Estimates of earthquake-related costs at a few localities are attempted. A reasonable assessment of the economic impact of past earthquakes would make them more existent outside the seismological community.

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them can be difficult. Estimates of earthquake-related costs at a few localities are attempted. A reasonable assessment of the economic impact of past earthquakes would make them more existent outside the seismological community.

S06b - Pre-Instrumental Earthquake Data

Quantitative evaluation of source parameters of historical earthquakes in southern Africa

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Macroseismic intensity information is important in the evaluation of historical seismicity. In an effort to improve the current South African earthquake catalogue, available macroseismic information of historical and early instrumental period earthquakes were used to determine epicentres and magnitudes of 46 earthquakes. Each of them had at least eight Intensity Data Points (IDPs). The IDPs were dominated by relatively low intensity values, which are consistent with a stable continental region. The source parameters were computed using state-of-the-art 3rd generation techniques. The quality of obtained solutions was greatly influenced by the spatial distribution of the IDPs, which was not uniform for all the events, with some events having clustered IDPs whilst others were linearly distributed. As a result, a quality ranking system of the results was developed to give an indication of the confidence in the results. Of the 46 earthquakes analysed, 36 had good quality results. The methods used were also checked by comparing solutions obtained using macroseismic data to those obtained for the same events but using instrumental data. Twelve events analysed in this study are new events that were not in previous catalogues. The results obtained help in improving the earthquake catalogue of the region, as there is an increase in the number of events recorded in the historical and early-instrument period. This kind of work and results obtained highlight the value of seeking out additional contemporary sources in order to revise the source parameters of earthquakes for which no or only very limited instrumental information is available.

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Coseismic and postseismic deformation associated with the 17th Century megathrust earthquake along the Kuril Trench estimated by diatom analysis

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A method to construct the history of past crustal deformation based on diatom analysis was developed, and the amount of coseismic and postseismic deformation associated with the 17th Century megathrust earthquake in Toberi marsh, Tokachi, Hokkaido, was estimated. The cores including the tsunami deposits at an altitude of 2.5-3.0 m (TP) inferred that subside trend continued before the earthquake and it turned to uplift trend after the event. Since both of the trends are gradual, the coseismic deformation does not seem to be significant. On the other hand, Pseudopodosira kosugii, which distributes the intertidal to supratidal zone, is most abundant on the horizon of the tsunami deposits. Present habitat distribution of Pseudopodosira kosugii in the same marsh revealed that the upper distribution limit and mode were 0.8 to 1.3 m (TP) and -0.2 to 0.3 m (TP), respectively. Prehistorical uplift can be estimated from the current elevation of the limit and the mode of this diatom in the core. The amount of the uplift in Toberi march after the 17th Century event was ca. 1.5 m. That was constrained by using both the distribution limit and the mode of cores from five survey points in the marsh. Information about the crustal deformation after the 17th Century event is useful for the evaluation of source models of the earthquakes that is used for tsunami hazard assessment along the Pacific coast of Hokkaido.

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Seismic activity in southern Miyagi Prefecture in the 18th century revealed from "Takano Family Record”

DOI: 10.57757/IUGG23-4735 - LINK

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Collaborative Research Organization for Historical Materials on Earthquakes and Volcanoes , Tokyo, Japan

"Takano Family Record” is investigated to reveal seismic activity in southern Miyagi Prefecture in the 18th century. "Takano Family Record" is a diary recorded by the successive heads of the Takano family between 1696 and 1782 and is included in a published collection of historical documents on earthquakes in Japan. About 150 days of felt records are newly found from our investigation of microfilmed original records kept in the library of the Graduate School of Arts and Letters, Tohoku University. Comparison between the number of felt earthquakes recorded in the "Takano Family Records" that observed by modern observations shows that the author of the "Takano Family Records" recorded earthquakes of JMA seismic intensity 2 or higher, as well as some earthquakes of intensity 1. "Takano Family Records" also contains descriptions of earthquake damage. Location and magnitude of the May 4, 1767 and October 22, 1767 earthquakes are reexamined from distribution of damage and felt records as well as the number of aftershocks.

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Voices of foreign residents in Yokohama and Tokyo at the time of the 1923 Kanto earthquake

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[2]*The University of Tokyo, Earthquake Research Institute, Tokyo, Japan*

On Saturday the 1st of September 1923 at a few minutes to noon, when the Kanto earthquake occurred, the foreign population of the harbor of Yokohama reached 2,500 people of different nationalities, and a similar presence was in Tokyo, which as the capital hosted the officers of embassies, consulates and trade companies. These foreign residents left impressive records of the earthquake occurrence, as well as the fire and tsunami that followed. As far as we could ascertain, their accounts have not been used yet to compile either the official reports or the published monographs on social and scientific aspects, works that mostly relied on and referenced the news press and official Japanese statements. To add a different viewpoint to the overall understanding of this earthquake, we concentrated on the considerable quantity of documents now stored at The National Archives (Kew Gardens, UK) and at the Affaires Etrangers-Archives Diplomatique (La Corneuve, Paris, France) produced by British and French diplomats as well as foreign residents of different nationalities who were in Yokohama and Tokyo at the time of the earthquake. The most significant testimonies from both cities are presented and compared, and the role in the relief actions of the British Royal Navy and of ships of other countries are put in the foreground. The immediacy of the descriptions they contain and the details they supply bring us back to the shaking and shocking moments experienced by the people living in Yokohama and Tokyo one hundred years ago.

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S06b - Pre-Instrumental Earthquake Data

Recurrence of Kanto earthquakes before 1923 and probability of future occurrence

DOI: 10.57757/IUGG23-0126 - LINK

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The Kanto earthquakes (M~8) recur along the Sagami trough, where the Philippine Sea plate subducts beneath the Kanto region. The most recent event was the 1923 earthquake which caused the worst earthquake disaster in Japan with ~105,000 casualties. The penultimate, 1703 Genroku earthquake caused larger crustal deformation and worse tsunami disasters in the southern Boso peninsula. Historical documents and tsunami deposits indicate that the 1293 Showo earthquake was also a Kanto earthquake. The 1495 Meio earthquake, considered to be confused with the 1498 earthquake along Nankai trough, may be another Kanto earthquake. Possibilities of the 878 and 1433 Kanto earthquakes have been also pointed out (Ishibashi, 2020, SRL). Marine terraces on the southern Boso peninsula indicate that the 1703 (Genroku) type earthquake recurred at approximately 2,300-year interval.

The Japanese government's Earthquake Research Committee (ERC) annually estimates and announces long-term forecasts, in terms of occurrence probability in the next 30 years. For the M~8 Kanto earthquakes, the probability was estimated as 0 – 5 %, based on historical and geological data, while the Genroku type event was estimated as 0 %. The recurrence interval is calculated as 209 years for the above six historical events, 261 years for the five (excluding 1433) events, 210 years for the four (excl. 878 and 1433 or 1495) events, and 315 years for three (1923, 1703 and 1293) events. The 30-year probabilities vary 0 – 12 % for the Brownian Passage Time model, and 9 – 13 % for the Poisson model.

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Monitoring the plate boundary using a vertical array of borehole and seafloor seismometers in the Nankai subduction zone

DOI: 10.57757/IUGG23-2236 - LINK

Takashi Tonegawa[1], *Eiichiro Araki*[1], *Yuya Machida*[1]
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We use ambient noise records obtained by a vertical array of seismometers at borehole and seafloor in the Kumano basin of the Nankai subduction zone, Japan, and examine whether S reflections from deep interfaces can be persistently detected or not. The vertical array contains a geophone at the seafloor and a borehole broadband sensor at a depth of 900 m from the seafloor. Our results show the retrieval of S reflections from the top of high velocity body above the megasplay fault, the megasplay fault itself, and the top of the subducting oceanic crust. The depths of these boundaries are 5–10 km from the sea surface. The arrival time of the S reflection for a polarization direction of N70ºE was faster, indicating that the direction is the fast polarization direction. We also investigated the temporal variation of the amplitudes of the S reflections at a slow polarization direction (N160ºE), and obtained temporal variations in amplitudes of the S reflections from the top of the high velocity body and megasplay fault for 1 year after 2016 off-Mie earthquake (Mw5.9) whose epicenter is ~30 km away from the vertical array. This may be related to fluid migration around these boundaries.

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S07a - Scientific Drilling and Downhole Monitoring – A Key to Understand Geohazards

Sensing fault zone at depth through Optical Fiber: Taiwan Milun-fault Drilling and All-inclusive Sensing (Taiwan MiDAS) project

DOI: 10.57757/IUGG23-3210 - LINK

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The Taiwan Milun fault zone located at the boundary between the Eurasian and Philippine Sea plates. This fault slips frequently and produced large earthquakes, as for example the Mw6.4 Hualien earthquake (6 February 2018). We map and observe the fault zone and its behavior at depth by high spatial resolution dynamic strain sensing with optical fiber. In 2021-2022, we drilled and cored the fault, and deployed a 3D multi-cross-fault fiber array comprising a borehole loop with a depth of 700 m (Hole-A, Hanging wall site, crossing the fault at depth), a surface array crossing the fault rupture zone using commercial fiber, and a second borehole loop of 500m fiber (Hole-B, Footwall site). The high spatial resolution from distributed acoustic sensing (DAS) and the retrieved core combined with geophysical logs allow us to characterize the structure on meter-scale. Within the Milun fault zone, we identified a 20-m wide fault core comprised of gray and black gouge in the core sample. DAS strain-rate records associated with the same depth as the fault core show a distinct amplification. The amplification ratio of 2.5-3 is constant as for all types of events (local, teleseismic), when compared to DAS channels at larger depth, related to a consolidated rock material. Although the fault gouge is narrow, the nature of the amplification in strain is due to its strong material contrast from fault gouge. This result may shed the light on the understanding of fault-zone dynamics in terms of remote earthquake triggering and near-fault ground motion.

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Scientific drilling and borehole investigations to study physico-mechanical properties of fault damage zones: a case from Koyna seismogenic zone, India

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Knowledge of physical and mechanical properties of subsurface faults is important for understanding the processes responsible for seismogenesis in a region. However, sampling of subsurface faults is quite challenging. Scientific drilling and downhole geophysical logging in active fault zones provide access to fault zone samples from depth as well as direct measurements of in-situ physical properties, leading to substantially improved characterization of such zones. Here, we demonstrate the wealth of information obtained from scientific drilling down to 3 km depth in the Koyna seismogenic zone and their implications for seismogenesis. Geophysical well log data has shown several fault damage zones in the basement which are characterized by low electrical resistivity, low bulk density, high neutron porosity, low Vp and Vs, high Poisson's ratio and low Young's modulus compared to the surrounding host rocks, especially below a depth of 2100 m. The data also reveal the presence of water-bearing horizons across most of the fault damage zones, indicating clear evidence of water percolation to deeper levels. Additionally, laboratory derived rock mechanical properties of intact and fault damage zone rocks also show significant variations in strength and static elastic properties of fault zone rocks from the intact host rock. Uniaxial cyclic loading tests on intact granitic rocks, located just above a fault zone, shows that elastic properties corresponding to the loading cycle close to failure is consistent with the elastic properties of the fault damage zone materials. The in-situ and laboratory datasets shed new light on the recurrent RTS in the region.

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Do the secondary precipitations control elastico-frictional deformation in Koyna-Warna seismic zone?

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The Koyna-Warna seismic zone, located in peninsular India is characterized by persistent seismic activity within an area of 20 km x 30 km area since the impoundment of the Shivajisagar water reservoir in 1962. In general, the hypocenters lie in the depth range 2-10 km, in the ~2.4-2.7 Ga granitic basement that underlies ~1 km - thick Deccan trap cover. Fresh core samples of the basement granitoids recovered from recent scientific drilling in the area have been studied. Physical studies suggest a brittle deformation sequence from cataclasite to fault breccia and fault gouge materials. These rocks contain meso- to microscopic scale fractures which are mostly inter- or trans-granular in nature. Widths of fractures vary from micrometer to centimeter scale, and the anastomosing nature facilitates fluid channelization potentially down to the hypocentral depths. Microstructural and geochemical studies suggest most of those are partially or completely sealed by ferruginous, siliceous and carbonate materials. Such secondary materials present in both crystal and amorphous forms imply a conducive setting for mineralization. The fractures dominantly control deformations nearby the hypocentral depths and secondary mineralizations. They also can be correlated with related changes in pore pressure and temperature during earthquakes.

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S07a - Scientific Drilling and Downhole Monitoring – A Key to Understand Geohazards

Scientific deep drilling in Koyna seismogenic zone (India) and geomicrobiological investigations: Insights into deep life and new opportunities

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Scientific deep drilling in the Koyna seismogenic zone (Koyna, India), sheds new light into the prokaryotic denizens of the deep, dark, igneous crust hosted biosphere, spanning the basaltic formations of Cretaceous volcanism to the Archaean granitic horizon (59-2913 mbs) of the Deccan Traps. These enigmatic polyextremophilic oligotrophic microorganisms possess unique genetic traits that allow chemolithoautotrophic metabolism under conditions of high temperature, pressure and severe energy and nutrient limitations while driving biogeochemical cycles of carbon and other elements. Obligately anaerobic acetogenic and microaerophilic hydrogenotrophic bacteria were enriched from these rocks using specialised nutrient media under high temperature (50-70 ℃) and CO_2 concentration (2-12% v/v). Their ability to assimilate hot CO_2 gas and metabolize gaseous $H_2$was investigated. 16S rRNA gene amplicon sequencing and predictive phenotyping have revealed the most abundant and metabolically productive genera to include *Moorella, Bacillus, Anarobranca*, *Thermoacetogenia*, *Thermonaeromonas*, *Desulfofundulus*, *Desulfovibrio* and *P aracoccus*. Phylogenetic Investigation of Communities by Reconstruction of Unobserved States 2 (PICRUSt2) analysis identified the most abundant autotrophic carbon fixation pathways to be reverse Krebs cycle, Calvin-Benson-Bassham cycle and Wood-Ljungdahl pathway; and major biosynthetic products as medium- and short-chain fatty acids, alcohols and antibiotics. Our research provides new insights into the geomicrobiological processes within the active seismogenic zone of Koyna and their possible correlation with various subsurface geophysical and geochemical properties. The study provides a better understanding of the overall system of such important geological provinces, highlighting the role of microorganisms and developing improved geomicrobiological methods to study such crystalline deep biosphere.

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S07b - Scientific Drilling and Downhole Monitoring – A Key to Understand Geohazards

We present ongoing experiments from the Bedretto Underground Laboratory for Geociences and Geoenergies, a unique research infrastructure in Switzerland

DOI: 10.57757/IUGG23-4314 - LINK

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The BedrettoLab is an open and extendable research infrastructure of ETH Zurich. It is located in the Bedretto tunnel in the Swiss Alps. Its primary mission is to advance transdisciplinary research in geoenergy applications, such as deep geothermal reservoir development in crystalline rocks, and in frontier geoscience research, such as earthquake physics and predictability. Laboratories in the deep underground bridge the gap between natural scales (kilometres and above) and the research-lab scale (centimetres). This facility is extremely valuable to Earth scientists for hypothesis driven, fundamental research as well as for technology demonstrations. In a natural and realistic setting, experiments such as inducing micro-earthquakes or reservoir stimulation at the scale of tens to hundreds of meters can be conducted under controlled and repeatable conditions, observed closely by hundreds of multi-parameter sensors. Currently, about 50 scientists, engineers and technicians are part of the core BedrettoLab Team.

Within the BedrettoLab two separate reservoirs, the so called Geothermal and Earthquake physics test-beds, have been developed and instrumented. Both test-beds are equipped with numerous boreholes either for stimulation purposes or monitoring. The monitoring boreholes are equipped with a high-resolution monitoring system.

Beyond the two dedicated test-beds, the Bedretto tunnel provides smaller experimental sites, such as individual boreholes (10-40m), geological outcrops, water inflows or hydro-bio-chemical sampling at various places along the 5.2km long tunnel.

We present latest results of ongoing experiments, projects in preparation and future perspectives.

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We present latest results of ongoing experiments, projects in preparation and future perspectives.

Heart of the volcano

DOI: 10.57757/IUGG23-4425 - LINK

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The near-field source region for volcanic eruptions is magma. At present, evaluating the risk of imminent volcanic eruption is based almost entirely on untested interpretations of data from a variety of remote sensors, separated from the eruption source by kilometers of solid rock. There is not even consensus as to what the source is: a mush chimney with regions of melt segregation? An accumulation of mostly melt? Or at what pressure it exists: hydrostatic? least principal stress? lithostatic (ρgh)? lithostatic + ΔP? In contrast to currently dominant views, accidental (the only kind there have been) drilling encounters with magma have found only melt-rich magma, no mush. Given this dangerous state of ignorance, we need to explore the source of volcanic eruptions directly. What is the state of this material before eruption, as revealed by quenching it in situ under pressure? What do the signals of unrest recorded at the surface actually mean about processes in magma-hydrothermal systems? The Krafla Magma Testbed (KMT), Iceland, an ICDP project, seeks to answer these questions with a doublet of boreholes to magma. The first will core and permanently instrument the interval from brittle rock to magma, establishing physical, chemical, and mechanical source conditions. This borehole will become a monitoring post for the second well, where intentional perturbation of pressure and temperature of the magma and flow testing of the expected high-enthalpy fluid will be matched to signals at depth and at the surface. Obviously, there are implications for exploiting superhot geothermal energy as well.

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Two small volcanoes, one inside the other: Geophysics and ICDP drilling of Bažina maar in western Eger Rift

DOI: 10.57757/IUGG23-4238 - LINK

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[6]Institute of Geophysics- Academy of Science, Electromagnetic, Prague, Czech Republic

Maar-diatreme volcanoes are small volcanic structures with a conical crater surrounded by a tephra-ring. They are formed by the explosive phreatomagmatic eruptions in a short time when groundwater comes into the contact with magma. We focus on the Bažina maar in the geodynamically active western Eger Rift (Czech Republic) and discuss results from multidisciplinary geophysical investigations calibrated by drilling in the frame of the ICDP Eger project (International Continental Drilling Program). Apart from the internal structure, we show how detailed pre-drill geophysical research contributed to a proper selection of the drill site which concluded in revealing unique structure of a maar volcano with several generations of eruptions. Two boreholes located in the maar crater evinced lithologies of the maar-diatreme filling and its contact with country rocks. They penetrated volcanic rocks and volcaniclastic deposits of the maar but also revealed pyroclastic cone with the olivine nephelinite feeding conduit. Such results are unique and disclose that the maar formation was followed by several subsequent eruptions within the maar. Further investigationsconfirmed long-lasting volcanic activity with very primitive magma and extremely low magma productivity, which distinguishes the western Eger Rift from other Cenozoic volcanic provinces in Europe. These results improve our understanding of volcanic processes, their significance is also general because they shed light on unique evolution of two volcanoes, one inside the other.

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S07b - Scientific Drilling and Downhole Monitoring – A Key to Understand Geohazards

Assessing the timing and cause of widespread iron oxidation through scientific drilling of the Colorado Plateau

DOI: 10.57757/IUGG23-3592 - LINK

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The origin of red beds is a longstanding, unresolved problem that has raised many contentious discussions. Multiple hypotheses describe how red beds form yet there is still much unknown about the ubiquity, timing, and source of the hematite minerals that color the strata. These uncertainties are complicated by an absence of such mass accumulation of hematite on today's continents and the lack of a depositional model that explains why the blue, red, and purple colors rapidly alternate through stratigraphic successions. We therefore need an explanation that can account for hematite production at a regional scale and the seriation of color at the bed scale. Solving this puzzle has implications for many pursuits (e.g., paleomagnetism, redox geochemistry, organic carbon burial) and can shed light on other intervals of the geologic past (e.g., Precambrian BIFs) and perhaps Martian hematite. In this study, I examine scientific drill cores of Late Triassic red beds from the Chinle Formation in the Petrified Forest National Park, Arizona. These units have been sampled for color through high-resolution core scans conducted at the CSD facility, Minnesota, USA. I compare the color data to hematite concentrations collected through lower-resolution stratigraphic sampling with a benchtop spectrophotometer. Stratigraphic variations in color and hematite are argued to be indications of an orbital climate control on red bed formation. Comparing the core data to stratigraphically equivalent outcrop intervals provides a set of predictions to test for the timing and amount of diagenetic hematite formed in sandstones and other units of the Colorado Plateau.

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Thermal effects of petro-physical parameters in the Guaymas Basin, Gulf of California: Case of study Ringvent

DOI: 10.57757/IUGG23-3508 - LINK

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Ringvent is a young shallow saucer-shaped sill intrusion emplaced in the Guaymas Basin in the Gulf of California, Mexico. It is an active hydrothermal cooling magmatic intrusion that allows the evaluation of thermomechanical processes involved in the emplacement of these structures in rift environments, practically in real-time.

This study aims to provide information about the mechanisms involved in sill emplacement by characterizing the physical properties in the contact zone between the sill and the host rock. The physical data used in this project was taken from ten logs and core samples drilled at the Ringvent site by the IODP 385 expedition. The data set includes measurements of density, permeability, p-wave velocities, and magnetic susceptibility that was analyzed, cleaned and plotted to find patterns in the sediment´s behavior around the sill contact area.

As a result of the analysis, we found that some of the factors that contribute to the emplacement of Ringvent are a porosity reduction above the sill, a decrease in the speed of the P-wave velocity, a slight decay in magnetic susceptibility, and the existence of a high-stress resistance layer above the sill.

These results were compared to another site in the Guaymas basin, where an older and deeper sill was emplaced, finding similar patterns. This correlation allows us to contribute to the discussion about the factors involved in sill emplacement and argue about if these observed changes are a result of thermal alteration by the sill, or in contrast, they are what determine the depth and shape of the sill.

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Imaging the weathering zone in Chile with active Radio-Magnetotellurics

DOI: 10.57757/IUGG23-0148 - LINK

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The interdisciplinary DeepEarthShape project focusses on the weathering zone with drillings and geophysical, geochemical and geobiological approaches. The weathering zone is the uppermost part of the Earth's crust where rocks and soils experience breakdown through the impact of air/gases, water and/or biological organisms. The full picture of weathering processes and our insight into the critical zone is still limited. Since some of the properties of the weathering zone seem to be linked with climate, a set of sites is studied within the framework of the DFG Special Priority Program 1803 belonging to different climate zones and thus experience different vegetation, precipitation and erosion.
We utilised a combination of seismics and Radio-Magnetotelluric (RMT) measurements along ~200m long profiles at three study sites in Chile. For the RMT experiment, we used a horizontal magnetic dipole transmitter together with a nearby MT station. To develop the method into an applicable tool for this kind of inter-disciplinary studies, we show RMT results at different stages: Experimental layout tuned with synthetic simulations, RMT data processing using machine learning approaches. And finally, we will show and discuss 2D and 3D inversion results together with geophysical logging data and lab measurements. First results indicate that we can image precipitation and shallow fluid enhanced zones and provide crucial information for other disciplines. Minor faults and folds can be traced into the active weathering zone and linked with surface and borehole information.

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S08a - Anthropogenic Seismicity

The Deccan Volcanic Province of India experiences all the three different types of earthquake sequences

DOI: 10.57757/IUGG23-0066 - LINK

Harsh K. Gupta[1]
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Mogi (1963) broadly classified the earthquake sequences in Type 1, 2 and 3. Type 1 earthquake sequences have no foreshocks. However, aftershocks follow. In Type 2 earthquake sequences the main shock is preceded by foreshocks, and the number of aftershocks as well as the duration of the occurrence of aftershocks increases. Type 3 of the earthquake sequence is a swarm kind of activity where the number and magnitude of shocks increases with the passage of time and then decreases after some time. The Deccan Volcanic Province (DVP) of India witnessed earthquake sequences belonging Type 1 (Latur earthquake of M 6.2 on 29 September 1993), Type 2 (Koyna earthquake of M 6.3 on 10 December 1967), and Type 3 (Palghar earthquake swarm 2018-2020). It has been proposed that the change in the mechanical properties in the shallow crust due to loading of water reservoir has caused the change from Type 1 to Type 2 earthquake sequence for Koyna. Similarly, intense rain is considered to cause the change to Type 3. However, how these changes occur is not well understood. There is a need for understanding the cause leading to three different characteristics of earthquake foreshock-mainshock-aftershock sequence for a single geological domain. It is hoped that the detailed near field studies of earthquakes being undertaken at Koyna will provide an explanation.

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S08a - Anthropogenic Seismicity

Recurrent reservoir triggered seismicity in Koyna, western India for the past six decades: What keeps it going?

DOI: 10.57757/IUGG23-3162 - LINK

Sukanta Roy[1], *Deepjyoti Goswami*[1], *Anup Sutar*[1], *Vyasulu V Akkiraju*[1], *Sunil Rohilla*[1], *Surajit Misra*[2], *Nagaraju Podugu*[1,3], *Thomas Wiersberg*[4], *Vishnu Chitralekha S*[1], *Matsyendra Shukla*[1], *Kunal Modak*[1]
[1]*Ministry of Earth Sciences, Borehole Geophysics Research Laboratory, Karad, India*
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Triggered seismicity in the Koyna region, starting soon after the impoundment of Shivajisagar water reservoir in 1962, has continued to this day. The activity, confined to 20 km x 30 km area and 10 km depth, is modulated by the annual loading and unloading cycles of the Shivajisagar and nearby Warna reservoirs. The 1967 M6.3 Koyna earthquake caused a NNE-trending surface rupture zone near Donichawadi, along which seismic activity in the past few decades is aligned.

To investigate the recurrent seismicity, a 3 km deep scientific borehole was drilled in the vicinity of the Donichawadi fault. Downhole measurements of physical and mechanical properties, borehole images, and composition of formation gases in the deep crystalline basement, combined with seismological data and laboratory geological and rock mechanical datasets provide new insights on the underlying conditions favouring recurrent seismicity: (i) Helium concentrations in the borehole suggest that the subsurface fault damage zones potentially associated with the Donichawadi fault. (ii) Drill core samples show evidences of repeated brittle deformations (iii) Water bearing zones are identified at multiple depths, providing strong evidence for percolation of water to deeper levels. (iv) Stress regime and earthquake focal mechanisms support transitional strike-slip to normal faulting environment. (v) The presence of optimally oriented, critically stressed and hydraulically conductive fractures creates conducive conditions for reactivation of faults with small changes in fluid pressure and/or frictional strength.(vi) Strain budget estimates from seismological and GPS data suggest that release of strain energy in terms of earthquake activity may continue for a longer time.

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Tomographic evidences for the triggering processes of earthquake swarms in Xinfengjiang Water Reservoir, China

DOI: 10.57757/IUGG23-1705 - LINK

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Induced seismicity has become a matter of concern for industry and nearby residents, as it poses significant risks to both property and human life. The Xinfengjiang water reservoir in China is a prime example of this, as it has induced earthquakes of magnitude greater than 6 and has experienced a yearly decline in dam stiffness. The potential safety hazards associated with induced seismicity have garnered significant attention. To address these concerns, a high-resolution 3D velocity and focal mechanism tomography study was conducted using a dense local seismic network. The study aimed to gain a deeper understanding of the underlying causes of induced seismicity in the area. The results show that fracture development beneath the dam area facilitated rapid fluid diffusion, whereas the presence of low-permeability striped bodies beneath the tail of the reservoir slowed fluid diffusion. A conceptual model was proposed linking the tomographic structure to the inducing process of the earthquakes, suggesting that an increased pore pressure is responsible for the seismic activity in both the dam and reservoir tail, while structural differences result in differing seismic activity characteristics.

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S08a - Anthropogenic Seismicity

Hydro-Seismicity in the Paraná Basin, SE Brazil: events induced by the opening of water wells and rainfall.

DOI: 10.57757/IUGG23-1588 - [LINK]

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Nine cases of earthquakes (1< M < 3.5) caused by the opening of water deep wells in the Paraná Basin, SE Brazil, are known since 1959. All occurred with wells drilled into the basalt layer to exploit confined aquifers.

The earthquakes start soon after the opening of the well, not after a long period of water extraction. The inducing mechanism is injection of water from the open surface aquifer into the confined deeper (100-200 m) aquifer. The uncased drilled well connects the surface and deep aquifers. These are clear examples of natural, gravity-driven fluid injection. The peak of seismicity occurs 2-3 months after the rainy season: rainwater recharges the surface aquifer, which in turn injects more water into the deeper aquifer increasing pore pressures at seismogenic depths. Earthquakes start near the drilled well and the active area expands with rates corresponding to seismic diffusivities from 0.02 to 0.7 m2/s, consistent with observed diffusivities worldwide.

Tens of thousands of deep wells have been drilled in the Paraná Basin: the hazard of seismicity induced by a deep well is very small. Most cases are in the NE part of the Basin close to several water reservoirs with induced seismicity, suggesting that both dam-induced and well-induced cases occur in a region of high neotectonic stresses.

The other natural earthquakes in the Basin occur mainly five months after the rainy season, especially in areas of flood basalt. Well-induced and rain-water seismicity show a common hydroseismicity character of the flood basalt layer.

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Spatial pattern of the seismicity induced by geothermal operations at the Geysers (California) inferred by unsupervised machine learning

DOI: 10.57757/IUGG23-2635 - LINK

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[2]*Politecnico di Milano, Dipartimento di energia, Milano, Italy*

We analyzed the earthquake density at the Geysers geothermal area (California) as function of time and space over a decade. We grouped parts of the volume of the geothermal area sharing similar earthquake rates over time; in this way, we found three concentric spatial domains labeled as A, B, C, moving from the inner- to the outermost domain, characterized by peculiar time-history of the earthquake rates and different Coulomb stress drops. The earthquake density decreases moving from domain A to C, and different b-values of the Gutenberg-Richter distribution appear for the domains A-B and domain C. We decomposed the mean earthquake rates into their independent components (ICs), which we model as the seismic response to some unknown triggering factors. IC1-2 appear to be straightforwardly related to the wastewater injection, while IC3 contains a secondary contribute from an unknown source. By simple modeling the earthquake source, we estimated that IC3 triggers about 1% of earthquakes of domain A and accounts for a yearly cumulative fault slip of about 7 mm. We broadly localized IC1 in the northern part of the geothermal area where most wells are located; IC2 is instead located about 4 km NW of IC1 source area. We model the earthquake pattern as principally due to stress transfer from the source of IC1 via a poroelastic mechanism.

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S08b - Anthropogenic Seismicity

Rethinking historical models of induced seismicity in Rocky Mountain House, Alberta, Canada: Is brine disposal to blame?

DOI: 10.57757/IUGG23-4941 - [LINK]

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Although most wells in Alberta have no correlation with induced earthquakes, the Rocky Mountain House Seismogenic Zone (RMHSZ) defies this trend. The RMHSZ is a long-lived (1970's to present) cluster of induced earthquakes located in west-central Alberta, Canada that has attracted attention following a stark increase in the regional seismicity rate after 2014. Seismicity in the RMHSZ has historically been linked to two mechanisms: poroelastic effects from gas production from the Strachan D3-A pool, a fractured Devonian reef; and natural earthquakes related to thrust faulting. The recent resurgence of seismicity brings the previously accepted poroelastic model into question, as gas production from the gas pool has ceased; new evidence suggests a nearby brine disposal scheme may be the culprit. This region is predisposed to favor induced seismicity from fluid injection based on overall sedimentology, diagenetic history, and complex structure, leading to increased seismic risk. Publicly available fluid injection data provided by geoSCOUT™ reveals the operator of the injector wells switched to a stratigraphically higher dolomitic zone, the Devonian Wabamun Group, in 2013; this timing coincides with the increase in seismicity.

We investigated the strength and nature of the relationship between recent seismicity and the production and injection history of nearby wells in the RMHSZ by applying a cross-correlation algorithm to injection volumes and earthquake counts. We found that recent seismicity does correlate with brine disposal in space and time; this method can be applied to other retroactive seismicity studies. On-site earthquake monitoring at RMHSZ should be undertaken in the future.

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S08b - Anthropogenic Seismicity

Stress features inferred from induced earthquakes in the Weiyuan shale gas block in southwestern China

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Stress features, particularly local stress field and earthquake stress drops, are important to understand mechanism of induced earthquakes. Since shale gas exploitations in 2015, the Weiyuan shale gas block has experienced frequent earthquakes. In this paper, we determine focal mechanisms of 257 events with M_L>1.5 by fitting three-component waveforms, invert for direction of maximum horizontal stress for two dense earthquake clusters, and then calculate stress drops for 17 earthquakes with moment magnitudes between 2.2 and 2.75 through the spectral ratio method. The focal mechanisms of all earthquakes are reverse faulting. The orientation of local maximum horizontal compressive stress is in the ESE direction, consistent with crustal movement indicated by GPS measurements. Both the focal mechanisms and microseismicity locations suggest the existence of steeply-dipping faults with dip angles of ~70º , which are relatively rare and difficult to slip under usual conditions, unlike major induced earthquakes with strike-slip or low-angle thrusting faults in the midwestern United States and western Canada. However, the steeply-dipping reverse events can be induced by large pore pressure from hydraulic fracturing. The stress drops range from 2.5 MPa to 54.7 MPa, comparable to those of potentially induced earthquakes in the midwestern United States. Our results imply earthquakes in the Weiyuan area are controlled by local tectonic stress and induced by large pore pressure from hydraulic fracturing, which advances our knowledge of reactivation of steeply-dipping reverse faults.

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Signatures of congregated injected fluid in Weiyuan Shale Gas Field, Sichuan, China

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Hydraulic fracturing (HF) is a viable technique to stimulate the productivity of unconventional hydrocarbon resources. However the mobility of injected fluid in HF plays a critical role in controlling fault reactivation and consequently induced seismicity. Yet tracking the injected fluids underground remains challenging because of the limited resolution in traditional approaches. In this study, we attempt to investigate the possible controlling mechanisms of induced seismicity in the Weiyuan shale gas field in Sichuan, China using a dense temporary seismic network that was deployed between April to June 2020. We apply the frequency index to analyze the impact of injected fluid on event waveforms and classify them based on the low/high-frequency components. We assess the potential controlling mechanism of these waveforms, including source, path, or injected fluid, and evaluate with waveform analysis. Our results reveal that low-frequency waveforms (LFW) are prominent in a certain azimuth range which rules out the possibility of source effects. Meanwhile, most of these LFW are constrained temporally and spatially and unlikely to be path effects. Furthermore, waveforms from nearly collocated earthquakes at different depths have distinct frequency contents. P phases are relatively unaffected, compared to highly attenuated S phases which suggest that absorption might be a key factor, instead of scattering. We identify a zone with congregated fluid near hydraulic fracturing platforms which might be responsible for LFW when ray paths encounter. Such fluid may trigger delayed seismicity or upward fluid migration which poses challenges to establishing an effective mitigation strategy for potential seismic risk.

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S08b - Anthropogenic Seismicity

Deciphering induced seismicity in southern Sichuan basin of China through comprehensive seismological tools

DOI: 10.57757/IUGG23-1161 - LINK

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Since the mass production of shale gas in Changning, Southern Sichuan basin of China in 2014, earthquake activity has increased rapidly, including the destructive 2018 Xingwen 5.7 and 2019 Gongxian 5.3 earthquakes, which are among the largest induced earthquakes worldwide. Because of the limited access to the industrial fracturing parameters, we have to rely on comprehensive seismological tools to decipher what mechanisms likely induce earthquakes in southern Sichuan basin, which include seismic location, focal mechanism determination, coseismic slip inversion, and seismic tomography.

Our seismic data mainly comes from a local seismic array including 10 4.5-Hz geophones covering the Changning shale gas block that has the area of ~50 km by ~20 km. In 2019, this array detected more than 40000 seismic events by applying an STA/LTA technique. Among these events, we selected ~11600 events with clear P and S arrivals for location and tomography. The relocated events are clustered in swarms and show vertical lineations beneath the target shale reservoir layer. We also selected 30-40 events for each swarm and determined their focal mechanisms by a full waveform matching method. From these focal mechanisms, stress inversion is conducted to determine the principal stresses and excess fluid pressures for each earthquake. Three-dimensional Vp, Vs and Vp/Vs models were determined for the shale gas block by the double-difference seismic tomography method. These joint analysis results show that these earthquakes are most likely induced by increased pore pressures on the seismogenic faults due to the presence of water and/or gas.

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Spatial clustering of induced seismicity controlled by the pre-existing faults and fractures in the southern Sichuan Basin of China

DOI: 10.57757/IUGG23-4936 - LINK

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The surge of seismic activity in the recent years has been attributed, at least partly, to intense hydraulic stimulation activities associated with the exploitation of unconventional natural gas resources in the southern Sichuan Basin, China. We have deployed a dense seismic array, which consists of 30 broadband seismometers with station spacing about 2 km, from December 2020 to March 2022 in the Weiyuan shale gas block within the southern Sichuan Basin. In this study, we systematically detect and locate 52210 earthquake events using LOC-FLOW framework and compute focal mechanisms of small to medium events (M>2). The enhanced catalog, with a maximum ML of 3.6 and a completeness magnitude of 0.5, generally includes two distinct prolonged earthquake sequences. The temporal migration of the earthquake sequences is highly correlated with fracking operations of two well pads both spatially and temporally. The events have focal depth ranging from 2 to 6 km, extending from the injection zone downward into the underlying crystalline basement. The focal mechanisms exhibit predominant thrust faulting, with P-axis subparallel to the maximum horizontal compressional stress direction in the region. Moreover, the lineation of earthquake clusters is also clearly associated with the apparent fault zones identified by ant tracking algorithm of a 3D seismic reflection survey, indicate reactivation of a subsurface thrust fault system. These results suggest that the spatially clustered earthquake sequences are driven by pore pressure diffusion related to hydraulic stimulation and strongly controlled by pre-existing faults and fractures.

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S08c - Anthropogenic Seismicity

Tectonic Strain Rate and Induced Earthquakes in Oklahoma: Implications for Regional Seismic Hazard

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In recent decades, the magnitude and harm of injection-induced earthquakes (IIE) due to anthropogenic activities have gradually increased, which has evolved into a global problem. However, the triggering mechanism of induced earthquakes is complicated, and there are significant spatial differences and time delays between the pumping areas and the areas where the induced earthquakes are concentrated, not all injections induce earthquakes, and it is not uncommon for regions with strong injections to remain seismically silent. To explore the controls on IIE, we compare geodetically derived tectonic strain rates with seismicity in Oklahoma where injections are prevalent. Results demonstrate that induced earthquakes are high in areas with moderate tectonic strain rates, while areas with high seismic moment release are consistent with areas with moderate tectonic strain rates, indicating that the regional tectonic is the fundamental cause of IIE. Moreover, the moment rates released by induced earthquakes approach even exceed the tectonic moment rate in the IIE-rich zone. We thus argue that injections indeed causes a large number of induced earthquakes and local seismic hazard in the short term, but limits the potential for larger future earthquakes by depleting the shallow tectonic moment.

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S08c - Anthropogenic Seismicity

The Nesjavellir (Iceland) geothermal production area: a detailed study of the recent seismicity

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Nesjavellir geothermal field is located in the northern part of the Hengill central volcano in South West Iceland. Electricity and hot water for district heating is currently produced by OR-Reykjavík Energy at two power plants around Hengill, Nesjavellir to the north and in Hellisheiði to the southwest. The seismicity recorded in the area is due to volcano-tectonic processes, natural geothermal activity and geothermal production.

The aim of this work is to deepen the understanding of the mechanisms of generation of seismicity through the study of the properties of the medium, it's variations over time and the kinematic characteristics of earthquakes.

Below Nesjavellir low Vp/Vs ratios and low b-values are observed at shallow depth (due to low Vp). High Vp/Vs ratios and high b-values are observed between 3.5 and 6 km depths (due to high Vp and low Vs), which is in correspondence with the deepest seismicity characterized by a higher percentage of small events. Our results suggest the coexistence of distinct mechanisms that control seismicity. From 4D analysis we observe the evolution of seismicity and a corresponding variation in the elastic medium properties as a function of the depth.

This work has been supported by PRIN-2017 MATISSE project, No 20177EPPN2, funded by Italian Ministry of Education and Research.

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S08c - Anthropogenic Seismicity

Physical modeling of injection-induced earthquakes in fractured rocks

DOI: 10.57757/IUGG23-3111 - LINK

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Induced seismicity has been a major challenge for engineering subsurface reservoirs. Particularly, hydraulic stimulation of Enhanced Geothermal Systems (EGS) is typically accompanied by seismic events that may be felt by public and even include damaging earthquakes. Massive fluid injection reactivates the pre-existing critically stressed faults and releases the strain energy by seismic slip. In densely fractured rocks, induced seismic sequence is jointly controlled by the fracture network geometry and the activated coupled hydromechanical processes. However, the physical linkage between geometrical attributes of fracture network spatiotemporal and magnitude distribution of induced seismicity is not fully understood. A physical understanding may define constraints over the maximum induced earthquake magnitude, which is a crucial parameter for seismic risk and hazard assessment. Here, we used stochastically generated discrete fracture networks (DFN) that represent the natural fractures as (poly)lines in a two-dimensional cross section. Various DFNs were generated over two orders of magnitude in length scales (1-100 m) to cover the observed length distribution in outcrop analogues. Then, we utilized a hydromechanical model to resolve the activated processes by fluid injection. The occurrence of seismic and aseismic slip was obtained by post-processing of the resulting displacement field. The preliminary investigations revealed the significant role of connectivity on the spatial distribution of seismic events. However, a sensitivity study is required to clarify the impact of unknown fracture network attributes (length and spatial clustering) on the characteristics of seismic sequence (b-value). The results of the analysis might have significant implications injection-related activities such as enhanced geothermal systems.

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S08c - Anthropogenic Seismicity

Spatiotemporal 4D configuration of water loads in dams and effects on stress and seismicity: Reservoirs of Aguamilpa, Itoiz, and Pirrís

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Among the key aspects for the analysis of artificial water Reservoir-Triggered Seismicity (RTS) is the adequate setting of the 4D spatiotemporal distribution of water loads, usually based on the Digital Elevation Models (DEMs) of the reservoir basin, and the observed temporal evolution of the water levels. Somehow, in some cases, the access to a detailed lake bathymetry for old reservoirs is generally limited.

Here we study the 4D spatiotemporal evolution of the stress changes as a function of the 3D configuration of the bathymetry, and the temporal changes in the water level in dams, using real and theoretical 3D DEMs. First, surface loads are modeled using 3D theoretical configurations for the bathymetry and water levels time evolution, considering the actual aspect ratio of the lakes. Stress changes (ΔCFS), are computed for an elastic halfspace, calculated using the full 3D stress tensor. Then, stress changes from theoretical models are compared with those produced by the real DEMs of the dam. The analysis is carried out for three different reservoirs: the Aguamilpa reservoir in Mexico, with a storage capacity SC=5480 hm3, the Itoiz reservoir in Spain, with a SC=418 hm3 and the Pirrís reservoir in Costa Rica with a SC=30 hm3. Stresses are compared with the corresponding seismic series occurred after the initial filling of the three dams. Results show that theoretical models adequately reproduce the main effects of surface loads even at relatively shallow depths, showing their suitability for the analysis on the possible induced shallow seismicity.

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Array-derived rocking and vertical ground motion scaling relations from seismicity induced by the 2018 Espoo/Helsinki geothermal stimulation

DOI: 10.57757/IUGG23-2868 - LINK

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The observation of ground motions excited by induced earthquakes near urban areas is of significant engineering importance. During the 2018 geothermal stimulation in the Otaniemi district of Helsinki, Finland, five seismic arrays consisting of 3 to 25 three-component geophones were deployed with interstation distances of 50 meters to record ground motions of 6-km deep induced events. This dataset provides an opportunity to study the ground motion patterns in the low-attenuation environment of the Fennoscandian Shield. The translational seismograms are used to calculate rotational motion for ~400 events with local magnitudes ranging from -0.5 to 1.8 using the seismogeodetic method. We evaluate the relationship between array-derived ground rocking rate (GRR) and vertical ground acceleration (VGA) associated with direct body waves. The robustness of the GRR estimates in the 2-15 Hz frequency range are assessed by comparing the VGA waveforms to the GRRs from the full arrays and to the GRRs from subarrays with different wavelength-to-aperture ratios. By rotating the two perpendicular components of the GRRs, we obtained the radial-transverse coordinate system that minimizes the GRR values on the radial component. We, find different P- and S-wave propagation directions that deviate from the theoretical back-azimuth of the earthquakes, and variations in the apparent body wave velocities beneath the arrays that we attribute to local propagation effects. While the deployment of broadband rotational sensors for wavefield gradiometry analyses is anticipated to become a common practice in the near future, this study provides a low-tech and band-limited experimental verification of the theoretical scaling models.

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S08c - Anthropogenic Seismicity

Earthquake-induced anomalies and recovery phenomena in groundwater system from the 2017 MW 5.5 Pohang earthquake in South Korea

DOI: 10.57757/IUGG23-0401 - LINK

Jaeyeon Kim[1], Kang-Kun Lee[1], Dugin Kaown[1], In-Woo Park[1]
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The 2017 M_W 5.5 Pohang earthquake was one of the largest earthquakes triggered by hydraulic stimulation for an enhanced geothermal system. This study aims at investigating hydrogeochemical and microbial evidence of earthquake-induced anomalies and recovery phenomena. Generally, groundwater level changes have been used as indicators, however, these have limitations for identifying the anomalies that cannot be interpreted comprehensively as pore-elastic behavior of aquifers. In this study, we analyzed hydrogeochemical data, including environmental isotopes (^{18}O, ^{2}H, Sr, and ^{222}Rn), and microbial diversity with time-series data of groundwater level. The physical modeling for pore pressure changes was also employed. The results showed that the wells near the epicenter had the notable changes in groundwater level, which are corresponded with the distribution of pore pressure changes from the modeling, whereas the other wells had abnormal patterns in the data of hydrogeochemistry and isotopes. These isotopic anomalies could suggest possible mechanisms underlying the responses to the earthquakes such as sea water intrusion, water-rock interactions, shallow and deep groundwater mixing, and deep fluid upwelling. With regard to the recovery phenomena, the hydrogeochemical and microbial results showed that shallow groundwater system has probably recovered within 2 years, whereas the geothermal well, with deep casing, did not recover to its original groundwater quality within 4 years, suggesting the management for a more extended period.

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Pressure diffusion controls maximum earthquake magnitudes induced by geo-energy applications

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It is an open question if maximum induced earthquake magnitudes can be determined based on knowledge about operational parameters, subsurface conditions and physical process understanding. We analyzed a global compilation of earthquakes induced by hydraulic fracturing, geothermal reservoir stimulation, water disposal, gas storage and reservoir impoundment. Our analysis showed that maximum magnitudes scale with the characteristic length of pressure diffusion in the brittle Earth's crust. An observed increase of the nucleation potential of larger magnitude earthquakes with time is likely governed by diffusion-controlled growth of pressure perturbed fault sizes. Numerical and analytical fault size modelling confirmed the findings. Finally, we derived scaling laws for the maximum possible and maximum expected magnitude for induced seismic hazard and risk forecasting and management.

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S08d - Anthropogenic Seismicity

Time-dependent seismic hazard analysis for induced seismicity based on a 3D ETAS model

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Induced earthquakes have peculiar characteristics such as relatively shallow depths, small-to-moderate magnitude, correlation with field operations, non-GR recurrence law, and eventually non-homogenous Poisson recurrence time. Thus, when dealing with induced seismicity, the standard Probabilistic Seismic Hazard Analysis (PSHA) has to be modified.

This work aims at exploiting the information carried by the ongoing induced seismic sequence in quasi-real time to provide spatio-temporal predictions of ground shaking in a prescribed forecasting interval (in the order of days). First, the workflow adaptively updates the seismicity forecasts based on the incoming information as it becomes available. The clustering of seismic events in volume (3D seismicity) and time is modelled based on an Epidemic Type Aftershock Sequence (ETAS) model. The proposed 3D ETAS model encompasses a decoupled depth-area volumetric probabilistic kernel. The ETAS parameters will be re-calibrated to take into account non-GR long-term temporal boundary conditions in case of induced seismicity.

Second, the PSHA is performed using proper ground motion prediction models (GMPE). By combining the time-dependent seismicity rates provided by ETAS model and the mentioned GMPE, PSHA in a prescribed forecasting interval is adopted for calculating the mean rates of exceeding certain ground-shaking levels.

The procedure is demonstrated through retrospective hazard forecasting of induced seismicity recorded at the Geysers geothermal field in northern California in the time period of 2011-2015 during fluid injection in the vicinity of Prati 9 and Prati 29 injection wells.

This work has been supported by PRIN-2017 MATISSE project No 20177EPPN2, funded by Italian Ministry of Education and Research.

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S08d - Anthropogenic Seismicity

A Coulomb Stress response model for time-dependent earthquake forecasts: Application to the Groningen gas field

DOI: 10.57757/IUGG23-0926 - LINK

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We have recently developed a new physics-based seismicity model assuming pre-existing populations of faults that respond to changes in Coulomb stress. In contrast to the traditional Coulomb Failure (CF) model, which assumes instantaneous triggering when stress exceeds a threshold value, the new model replaces instantaneous triggering with an average time to failure that depends exponentially on the absolute stress value. The prediction for critical pre-stress conditions is identical to the widely used rate-state (RS) friction model. Thus, CF and RS predictions are both special cases of the new model. However, the new stress response model can also account for subcritical initial stress conditions, which are particularly relevant for induced seismicity in intraplate regions.

Here we show the application of the new model to the Groningen gas field, which is one of the largest onshore gas fields in production in Europe and a frequently considered site for the study of induced seismicity. The long delay between the start of production and the onset of seismicity indicates subcritical pre-stresses. We estimate the pre-stress distribution based on the background stress field and the existing fault structure. Using this pre-stress distribution and the estimated temporal evolution of the 2D stress field in the reservoir, we show that the delayed onset, the peak in 2013-2015 and the recent decline in observed seismicity are well explained by the model.

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S08d - Anthropogenic Seismicity

Magnitude complexity of earthquake sequences resulting from anthropogenic activities

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Human activities exploiting geo-resources can cause moderate to strong earthquakes and result in significant economic and social impacts. It was shown (Urban et al. Pure Appl. Geophys. 173, 2016) that because such anthropogenic seismicity was controlled by complex technological factors, its magnitude distribution might deviate from the exponential distribution of the Gutenberg–Richter (G-R) law. Here, we investigated the deviation of the magnitude distributions from the G–R law for twelve earthquake sequences of anthropogenic seismicity, accessible on the "EPISODES" platform of EPOS Thematic Core Service Anthropogenic Hazards (https://tcs.ah-epos.eu/). The sequences include earthquakes induced by reservoir impoundment and hydraulic injection, as well as acoustic emissions induced by repetitive cooling cycles. We examined the magnitude distributions of space–time clusters of seismicity following variations of the inducing processes, ensuring the stationarity of the seismic process by appropriate temporal window selection. Subsequently, we assessed the deviation from the G–R law via the Anderson – Darling test.

The results showed that the magnitude distribution of anthropogenic seismicity deviated from exponentiality regardless of the causative technological factors. They point to the need to consider alternative magnitude distribution models when calculating seismic hazard parameters, as incorrect models can impose unacceptable errors on hazard estimates.

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S08d - Anthropogenic Seismicity

Waiting times distribution for fluid-injection induced seismicity

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Waiting times distributions between successive earthquakes have extensively been studied to provide insights into the physical mechanism of seismogenesis and to effectively assess seismic hazard. While in tectonic seismicity the waiting times distribution is well-defined as the superposition of Omori-like aftershock sequences on correlated and/or random background activity, in induced seismicity associated with fluid-injections in the subsurface, the underlying physical mechanism remains ambiguous. Herein, we analyze the waiting times distributions in various cases of fluid-injection induced seismicity in deep geothermal reservoirs, as in the Cooper Basin (Australia), Basel (Switzerland), Soultz-sous-Forêts (France) and Espoo (Finland). In all cases that we study, the probability densities of waiting times present broad distributions with asymptotic power-law behavior, indicating clustering effects at intermediate and long-time scales. At short-time scales, however, clustering effects in most of the cases are either weak or absent, suggesting that seismic clustering due to aftershocks is missing. In the Habanero field (Cooper Basin), on the other hand, short-term clustering is also present, implying the interplay of various physical mechanisms in the evolution of induced seismicity. The observed scaling behaviour, in all the cases, can well be described with a stochastic model that incorporates nonstationarities and memory effects in the evolution of seismicity, contrasting a random Poisson process.

Acknowledgements

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 00256).

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S08e - Anthropogenic Seismicity

Studying anthropogenic seismicity and related hazards by means of the EPISODES platform, an integrated infrastructure of EPOS TCS Anthropogenic Hazards

DOI: 10.57757/IUGG23-0515 - LINK

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Thematic Core Service Anthropogenic Hazards Department, Warsaw, Poland
[2]AGH University of Science and Technology, Academic Computer Centre Cyfronet, Kraków, Poland

Anthropogenic seismicity is an unwanted by-product of the technological operation of humans. The socio-economic impact of the induced seismicity is significant. Induced earthquakes can cause material loss, injuries, and fatalities. Data access is necessary to assess and mitigate the associated hazards. To respond to the need of the scientific community, the Thematic Core Service Anthropogenic Hazards (TCS AH) has been created within the framework of the European Plate Observing System, a solid earth science European Research Infrastructure Consortium (ERIC). TCS AH is a consortium of 14 institutions from Europe and beyond. TCS AH provides access to a novel e-research infrastructure, the EPISODES Platform, to foster research and training on induced seismicity and geo-hazards related to the exploration and exploitation of geo-resource. The EPISODES Platform is connected to international data nodes which offer open access to multidisciplinary datasets called episodes. Episodes comprise geoscientific and associated data from industrial activity along with a large set of embedded applications for their efficient data processing, analysis, and visualization. The EPISODES Platform also opens the possibility to create new applications and combine implemented applications with the user's codes. We present the current results of the TCS AH research infrastructure integration indicating the benefits of their usage for science, education, and innovation.

This work was conducted in the frameworks of (1) the TCS Governance and Coordination Collaboration Agreement 2021-2023 between EPOS-ERIC and the Institute of Geophysics, PAS (NUMBER 01– CA-TCSGOV-AH), and (2) the project "TCS AH," financed by the Polish Ministry of Education and Science, (Number 2021/WK/09).

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S08e - Anthropogenic Seismicity

The QuakeMatch Toolbox: Using waveform similarity to enhance the analysis of microearthquake sequences at Swiss geothermal projects

DOI: 10.57757/IUGG23-3821 - LINK

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[2]*Università degli Studi di Napoli- Federico II,*
Dipartimento di Scienze della Terra- dell'Ambiente e delle Risorse, Naples, Italy

Many Swiss microearthquake sequences have been analyzed using relative location techniques, which often allowed constraining active fault planes and tectonic processes that drive seismicity. Yet, often the number of located earthquakes was too small to infer details of the space-time evolution of the sequences or their statistical properties, and thus resolve clear seismicity patterns and their driving mechanisms.

We present a nearly automatic workflow that combines well-established seismological analysis techniques to improve the completeness of detected and located earthquakes of a sequence. Starting from a manual catalog (magnitude of completeness, Mc ≈ 1.0−1.5), we assemble a template set and perform a matched filter analysis on a single station with highest SNR. This allows us to detect events of local magnitude $M_L < 0.0$. The waveform similarity is further exploited to derive detection magnitudes. The enhanced catalog is then statistically analyzed to derive high-resolution temporal evolutions of the Gutenberg−Richter a- and b-values, and consequently the occurrence probability of larger events. Strong events are located using relative double-difference, which usually improves the number of well-relocated events by a factor of 2−5.

This workflow allows us to significantly enhance the analysis of spatiotemporal behavior of natural and induced microearthquake sequences, which we use to monitor commercial and scientific fluid injections in near real-time. We implemented this workflow in the open-source Python/PostgreSQL toolbox **QuakeMatch**. We discuss the capabilities of QuakeMatch with examples of induced microearthquake sequences associated with various geothermal projects monitored by the Swiss Seismological Service in the framework of the GEOBEST2020+ project.

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S08e - Anthropogenic Seismicity

Activation of a natural fault zone in the BedrettoLab

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[1]ETH Zurich, Department of Earth Sciences, Zurich, Switzerland
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[3]INGV Roma, Sismologia e Tettonofisica, Roma, Italy
[4]RWTH Aachen, Engineering Geology, Aachen, Germany

The Fault Activation and Earthquake Rupture (FEAR) project aims at activating a natural granitic fault zone in the BedrettoLab at the 100m scale. The goal is to observe and study earthquake rupture phenomena in a natural setting from unusually close distance.

The Bedretto Underground Laboratory for Geosciences and Geoenergies is a research laboratory in a 5km long tunnel in the southern Swiss Alps, with an overburden of up to 1.5km. At 2.4km into the Bedretto tunnel we have identified a ~2m thick natural fault zone. The fault zone consists of multiple distinct quartz and biotite shear fractures, some of which contain gauge layers of up to 5mm thickness. The fault zone is favourably oriented for rupture in the estimated present day background stress field.

In autumn 2023, we plan to excavate a side tunnel that runs parallel to the fault zone for ~125m. This tunnel will facilitate the installation of a very dense multi-domain geophysical monitoring system, directly on and around to the fault zone. After a detailed characterization of the fault zone and the host rock, and with the monitoring system in place, we plan to activate the fault via water injection in multiple injection boreholes, in a suite of experiments. If successful, the experimental setup will allow us to study a wide range of seismic and aseismic crustal deformation phenomena from up close, including rupture preparation and precursory signals, rupture nucleation, coseismic strain localisation, rupture growth and termination as well as the post-seismic response of the fault zone.

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S08e - Anthropogenic Seismicity

Investigating seismic repeater and (a)seismic fault dynamics using fiber optics in the Garpenberg ore mine, Sweden – FIMOPTIC project

DOI: 10.57757/IUGG23-2265 - LINK

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[2]*Institut de Physique du Globe de Paris, Université de Paris UMR 7154- CNRS, Paris, France*
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Seismic repeaters are a well-known phenomenon in natural seismotectonic environments but have been rarely observed in underground mines. Recent studies in the Garpenberg excavation mine (Sweden) have shown that repeaters may represent significant part of the total number of microseismic events (> 80 %). Accurate analysis, involving multiplet clustering, relocation, source parameter and mechanism estimation, and inter-event time analysis, suggest that seismic repeaters represent brittle frictional components of creeping, planar shaped, pre-exiting structures of several meters' length.

The accessibility and high recurrence rates of these repeaters provide a great opportunity to study and monitor repeaters in situ and to improve our understanding on seismic-aseismic coupling mechanisms in fault zones and potential pre-seismic precursory slip on faults asperities. In the framework of the FIMOPTIC project, we aim at monitoring the full seismic cycle of certain repeater targets using standard in situ strain monitoring combined with recent optic fiber technologies. In the first phase of the project, we currently investigate the exact location of some target repeaters using dense seismic arrays, as well as DAS and DTTS campaigns along optic fibers installed along the mine galleries. Once a accurate location is obtained and the geo-structural nature of the phenomena better understood, we aim at performing detailed in situ strain measurements along boreholes cross-cutting the faults zone (asperities) including a high resolution Faby-Pérot optical strain-meter with sensitivities in the nano-strain range at low frequencies (< 10 HZ). The presented study provides an update on these investigations and shares preliminary results.

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Exploring the potential of surface monitoring networks for induced seismicity in the Utah FORGE geothermal project

DOI: 10.57757/IUGG23-2796 - LINK

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Enhanced geothermal systems are a cornerstone in transitioning from fossil to renewable energy sources. However, applications of its potential are still rare, either due to economic reasons or concerns about induced seismic activity. The large-scale Utah FORGE project (Milford, Utah, USA) with a planned well-doublet reaching a depth of 2.5km in crystalline basement rock addresses both issues. Detailed microseismic monitoring of deep geothermal projects remains challenging and expensive when using additional deep monitoring boreholes. We explore the potential of cost-efficient surface or shallow-borehole (tens of meters) monitoring networks regarding the detection and characterization of injection-induced seismicity during three stimulation stages at Utah FORGE in 2022. The analysis relies on full-waveform-based methods for detecting, locating, and classifying events and inversions for focal mechanisms of the largest events. It also includes exploiting information from a multi-patch geophone nodal deployment via waveform stacking, which helps further lower the surface network's detection threshold. We compare our surface monitoring catalog to the official deep borehole monitoring catalog, which comprises ~2500 events between M -2.09 and 0.52. Preliminary results indicate that despite the higher noise level at the surface and the increased distance to the source area, we can reliably detect events down to M -0.7 using the surface networks. In the ongoing work, we investigate the resolution of seismicity patterns and evaluate the applicability of such cost-efficient surface networks for monitoring geothermal projects.

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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. The use of macroseismic intensity has grown as the hazard layer within essential USGS and others' real-time information products and even in presenting hazard maps in a form friendlier to nontechnical users. However, even with best practices, there are limitations to modern macroseismic data collection approaches. Whereas crowd-sourced intensities are robust for lower levels, they are poorly defined above intensity VII, where damage assessment requires knowledge of each building's structural system. Likewise, the United States, New Zealand, and others employ the Modified Mercalli Intensity (MMI) scale, which is consistent with—yet inferior to—the more recently developed European Macroseismic Scale (EMS-98). We report on an IMS Working Group meeting held in October 2022 at the USGS Powell Center to address these and other issues and to work towards an IMS. Workshop goals were, first, to harmonize the MMI scale with EMS-98 for the US and NZ—which share several similar building types—by considering those structures and associated damage grades not well represented in the current EMS-98 building vulnerability table. Second, formalize the process of augmenting EMS-98 with vulnerability classes appropriate for building types in other countries, thus promoting a scale that can be employed globally. Such efforts require expanding the EMS-98 explanatory documents. Lastly, we discuss how standardized earthquake-damage data collection worldwide—as part of an IMS—could facilitate hazard and risk analyses.

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S09a - Earthquake Ground Motion and Seismic Hazard

Utilization of crowdsourced macroseismic observations to distinguish “high-impact” from “low-impact” earthquakes globally within minutes of an event

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Rapid assessment of an earthquake’s impact on the affected society is a crucial first step of disaster management, determining further emergency measures.
We demonstrate that macroseismic observations, collected as felt reports via the LastQuake service of the European Mediterranean Seismological Center, can be utilized to estimate the probability of a felt earthquake to have a “high impact” rather than a “low impact” on the affected population on a global scale. In our fully data-driven, transparent, and reproducible approach we compare the distribution of felt reports to documented earthquake impact in terms of economic losses, number of fatalities, and number of damaged or destroyed buildings. Using the distribution of felt-reports as predictive parameters and an impact measure as the target parameter, we infer a probabilistic model utilizing Bayes’ theorem and Kernel Density Estimation, that provides the probability of an earthquake to be “high impact”. For 393 felt events in 2021, a sufficient number of felt reports to run the model is collected within 10 minutes after the earthquake. While a clean separation of “high-impact” and “low-impact” events remains a challenging task, unambiguous identification of many “low-impact” events in our dataset is identified as a key strength of our approach. We consider our method a complementary and inexpensive impact assessment tools, that can be utilized instantly in all populated areas on the planet, with the necessary technological infrastructure. Being fully independent of seismic data, our framework poses an affordable option to support disaster management in regions that currently lack expensive seismic instrumentation.

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S09a - Earthquake Ground Motion and Seismic Hazard

Semi-realtime scenario fault estimation judged by ground motion time histories

DOI: 10.57757/IUGG23-4786 - LINK

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To estimate a potential source fault after an earthquake is important for seismic hazard assessment (e.g., FinDer). Using pre-calculated ground motion time histories will be useful for earthquake evaluation to grasp which scenario earthquakes are similar to each other within a few hours to half a day when an earthquake occurs. We develop a method to compare observed ground motions by NIED K-NET/KiK-net with simulated ground velocities from the NIED J-SHIS database that for the Scenario Seismic Hazard Maps in the National Seismic Hazard Maps 2020, targeting active faults in Japan. Based on the comparison of velocity ground motion time histories with a 0.1-1 Hz band-pass filter, cross-correlation coefficients with/without amplitude normalization were obtained, and scenario fault candidates were ranked. We applied this method to the 2016 Kumamoto earthquake sequence. The fault selection for the foreshock worked well, supporting the proposed method. However, the mainshock did not select the ruptured fault identified by the ground truth. One of the reasons is the different dominant frequency between the observation and pre-calculated ground velocities, indicating the necessity of further adjustment.

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The shallow Mw 4.9 2019 Le Teil earthquake, France: Main ground motion features highlighted by comparison with ground motion models

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On November 11th, 2019, a moderate M_W 4.9 earthquake occurred in Le Teil in the southeast of France, inducing significant damage (VIII on the EMS98 intensity scale in some localities). This moderate earthquake occurred at a very shallow depth of 1-2 km and induced a surface rupture up to 15 cm uplift. Good quality recordings of this earthquake are available at numerous stations well distributed around the epicentre, with the nearest station 8 km from the rupture. These recordings were analysed to highlight any specific ground motion features related to the shallow depth of the earthquake with a focus on the residuals between observations and ground motion model predictions. The first trend emerging from the residual analysis is that observations are higher than predictions at 0.5 Hz and on the contrary, they are lower above 5 Hz. Looking at the spatial distribution of residuals, we highlight that their amplitude is closely related to their location. For example, at high frequencies, residuals are lower for sites in the southeast of France, which is consistent to the first order with regional attenuation maps. Source properties and regional geological characteristics could also be explored to explain the residual amplitudes in different frequency ranges. Finally, different phenomena could be involved to explain residuals, but it is not straightforward to conclude that one factor is dominant.

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S09a - Earthquake Ground Motion and Seismic Hazard

Comparison of various ground-motion prediction equations with the 2019 Mw6.4 Durres, Albania, earthquake

DOI: 10.57757/IUGG23-1053 - LINK

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Earth System Science Program- Academia Sinica and National Central University- Academia Sinica- Taipei 11529- Taiwan, Earth Science, Taipei, Taiwan Province of China
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The aim of the study is to analyze the existing ground motion prediction equations (GMPEs) applicable in Albania for horizontal peak ground acceleration (PGA) and spectral acceleration (SA). We present four sets of GMPEs evaluated for Albania using a dataset of instrumental strong-motion records from the November 26, 2019, Mw6.4 Durres earthquake. Besides the mainshock, the models are tested for foreshock and aftershock events of magnitude Mw>5.0. The GMPEs from Boore et al., (2014), Chiou and Youngs (2014), and Kotha et. al., (2020), provide a better fit to the ground-motion attenuation observed for the mainshock at distances up to 400 km, while Akkar et. al., (2014) fit better at a short distance. Along with the seismological aspects of the earthquake, we give an overview of the damages and social consequences, considering the engineering seismology source of data known as “Did You Feel It?” (DYFI) and the 1360 DYFI online citizen responses collected after the Durres event. The DYFI data are higher than instrumentation data, better represented using SA at 0.3s. By integrating the instrumentally observed data with the macroseismic observed data, we explore the importance of human response to the concept of ground shaking, demonstrating how this type of information can indeed reduce the gap in regions with a limited number of near-field stations. Therefore, this study makes a major contribution to the selection of GMPEs and provides a useful reference for the logic tree structure in subsequent seismic hazard assessment on both national and regional scales.

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S09b - Earthquake Ground Motion and Seismic Hazard

Developing international standards and guidelines for curating, disseminating, and validating simulated earthquake ground-motion data

DOI: 10.57757/IUGG23-2877 - [LINK]

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[2]Middle East Technical University, Civil Engineering, Ankara, Turkey
[3]United States Geological Survey, Earthquake Science Center, Menlo Park, USA

We are leading an effort to develop international standards and guidelines for curating, disseminating, and validating simulated ground-motion data. This effort is organized as a working group within the Consortium of Organizations for Strong Motion Observation Systems (COSMOS). In 2022 we held online workshops on 7-8 June and 20 October. The first workshop focused on curating and disseminating simulated ground-motion data. The second workshop focused on validating simulated ground-motions for engineering applications. We intend to form a technical committee to draft international guidelines and standards while continuing to engage stakeholders from across the globe through online and in-person meetings.

The key points from workshops include: (1) Numerous groups are generating simulated earthquake ground motions and making them openly available, however there is very little coordination among groups to provide consistent interfaces for searching and retrieving data; (2) Standardizing interfaces for metadata and data access should consider agile approaches that can adapt to changing capabilities and user needs while building upon existing efforts; (3) Participants advocated for a distributed architecture that would allow institutions to host and manage their own data while broadcasting their holdings to a combined catalog; (4) Validation of ground-motion simulations applies to the entire workflow for simulating earthquake ground-motions, including the rupture model, seismic velocity model, and seismic wave propagation software; (5) Metrics to evaluate the validation are application dependent; more research is needed to tie structural response characteristics to ground-motion characteristics; and (6) Validation results should provide a clear, transparent, quantitative assessment of the simulated ground motions.

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S09b - Earthquake Ground Motion and Seismic Hazard

The BELSHAKE database of earthquake ground motion in Belgium

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The BELSHAKE project aims to compile a database of ground motion in Belgium and to develop the capacity to model earthquake ground motion based on that. This database contributes to existing databases by increasing the coverage of low-seismicity regions. The current BELSHAKE database contains ~7000 records from 362 natural and induced earthquakes in Belgium and adjacent areas since 1985 with $M_L \geq 2$. It includes records from broadband, accelerometric, and short-period sensors operated by the Royal Observatory of Belgium. For each event, the relevant source parameters and station metadata are extracted from the ROB database, event-station metadata computed and waveforms capturing the complete event downloaded. The waveform library is structured in folders corresponding to each event, containing one file for each station. The metadata and ground-motion parameters are collected in a relational database. A dedicated python library provides a programming interface with the database and waveform archive, allowing reading and writing of metadata, and streamlining data import. All records have been visually checked to correct or eliminate problematic waveforms such as low signal-to-noise ratio, timing problems, disturbances, clipping, missing or incomplete phase windows, interruptions, and the presence of foreshocks or aftershocks. We use a combination of two windowing procedures, one to define P, S and coda windows, and the other to define noise windows. We are currently implementing a semi-automatic workflow to process the waveforms in a uniform way, which will allow to determine ground-motion parameters following international standards. In this contribution, we discuss the database and processing steps in more detail.

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Moment-Magnitude Definition for Pan-European Shallow Crustal Earthquakes: Impact on Fourier Ground-Motion Variability

DOI: 10.57757/IUGG23-4296 - LINK

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In a probabilistic seismic hazard assessment (PSHA) the estimated likelihood of rare/large ground-motions is controlled by the aleatory variability of the Ground-Motion Model (GMM). This variability is partly from the poor modelling of earthquake physics, and partly from the poor quality of GMM parameters. Here, we investigate the impact of the definition of moment magnitude (M_W) on GMM variability. Indeed, M_W can either be estimated directly from the moment-tensor inversion or deduced from other magnitude scales. However, for the same event, even the moment-tensor based M_W estimates provided by different agencies often differ – due to differences in computation methods, inverted data, and network configuration. Various strategies have been proposed to define a unique M_W value for each earthquake. In this study, we developed Fourier Spectrum GMMs using the pan-European Engineering Strong Motion database using two disctinct strategies to define M_W: (1) the EMEC approach (ranking of the M_W sources) preferring M_W from event-specific studies, and (2) the IRSN approach (ranking + unification) in which all M_W values are unified with those from the Global and Regional Centroïd Moment Tensor catalogs. We observe that the IRSN unified M_W achieves a 18% smaller between-event variability at low frequencies (e.g. 0.3Hz) compared to EMEC M_W. Such reduction in GMM variability makes a strong case for the use of M_W unification approaches in GMMs and in earthquake catalogs – the two blocks of PSHA.

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S09b - Earthquake Ground Motion and Seismic Hazard

Towards a reduction of the high-frequency uncertainty of ground-motion-models: Inventory of insufficiently taken into account phenomena that disturb seismic record

DOI: 10.57757/IUGG23-4598 - LINK

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Reducing the standard deviation of ground motion models (GMMs) is a challenge that has engaged the seismic hazard scientific community for many years with results that unfortunately do not match the dedicated efforts. The work of the last few years, allowing the processing of an ever-increasing amount of data with machine learning approaches, has allowed great progress towards the reduction of these uncertainties, nevertheless, the high frequency uncertainty remains large, especially for GMMs developed in the Fourier domain.

While these machine learning approaches are particularly promising, it is nevertheless necessary for the seismologist to provide them with the relevant parameters to test. In this work, we inventory a set of phenomena that disturb high frequency signals and that are not or rarely taken into account. We present a synthesis of recent results on different phenomena: small-scale soil-structure interaction generated by slabs or pillars often used to couple seismometers and accelerometers, depth effect, small-scale topography effect, seasonal variations. We discuss the interest of a better documentation of the installation conditions within the metadata associated to seismic motion databases.

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S09b - Earthquake Ground Motion and Seismic Hazard

Using mixed-effects regression to derive site-specific kappa from regional data; Applications to Turkey and California

DOI: 10.57757/IUGG23-2498 - LINK

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The kappa (κ) parameter represents the rate of high-frequency decay of recorded earthquake ground-motion spectra with respect to a theoretical source model. Its value at zero distance, κ_0, is usually used to isolate the site component of decay from the path-related attenuation. κ_0 has significant implications in ground motion simulations, adjusting ground motion models to different geological conditions, and site response analyses. κ measurements from regional seismograms at various site-to-source distances are often used to estimate the site-specific, zero-distance value of κ_0 through regression with distance. When combining several stations, there are two ways to do this, which we call here 'fixed-slope' and 'free-slope' methods. The 'fixed-slope' method enforces a common slope (i.e., distance dependence function) for a given region, as that is strongly related to the regional path attenuation characteristics (e.g., quality factor), and then allows for individual estimates (zero-distance intercepts) per station. In contrast, the 'free-slope' method allows for a station-specific intercept (κ_0) as well as slope. This study compares the two methods, using Turkey and California as study regions, and discusses the potential problems associated with both, such as the effects of variation in station density and number of records at each station. We propose using mixed effects regression as a way to overcome some of the limitations of the fixed- and free-slope methods, and to achieve reductions in the variability and bias of estimated κ_0.

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S09b - Earthquake Ground Motion and Seismic Hazard

Obtaining site effect-free hard-rock time series in Japan from the generalized inversion technique

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The computation of time series for hard-rock site conditions, either as input motion for site response calculations or for applications to installations constructed on this site type, is a crucial step for seismic hazard assessment. The current state-of-the-art is to apply physics-based corrections to surface motions to eliminate the influence of site effects for retrieving the underlying bedrock motion. Here we evaluate the application of the generalized inversion method (GIT) for deconvolving surface recordings to obtain hard-rock time series at the amplification-free seismic bedrock. The method includes an event-specific phase scaling approach on the surface recordings that takes changes in the signal duration between the surface and the seismic bedrock into account.

We choose a total of 90 KiK-net surface-downhole sites for validation which do not have a significant velocity contrast below the downhole sensors and with the latter being located at sufficient depth so that they are not significantly impaired by downgoing waves. By comparing the empirical predictions from surface recordings with time series that have been recorded at the downhole sensors, we assess the accuracy of the predictions. In contrast to empirical and one-dimensional modelling approaches, which significantly overestimate the level of hard-rock ground motion for frequencies greater than a few Hz, we find quite high correlations and small variations in both spectral shape and amplitude over the entire frequency range. This approach delivers a data set that facilitates the development of reference ground-motion models.

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Toward a regionalized ground motion model for shaking scenarios in Italy

DOI: 10.57757/IUGG23-4070 - LINK

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Several studies, conducted over the last 20 years, have shown that ground motion in Italy is characterized by a strong regional variability and, in particular, tectonic and geological factors play key roles in the definition of the observed differences. In the early 2000s, several researches (Castro et al. 1999, Malagnini et al., 2000; 2002) were focused on conducting systematic studies of the regionalization in Italy using local dataset of small magnitude recordings of the seismic sequences that occurred in Italy in the early instrumental epoch.

Recently, the availability of a large number of records from moderate-to-strong earthquakes on the entire Italian territory allowed us to review previous results, with the final aim of producing a new generation of Ground Motion Models (GMM) models for the calibration of shaking scenarios. In this work, the analysis of the residuals (logarithm differences between observations and GMM predictions) was exploited to describe the regional differences in terms of source and path effects across the country (Brunelli et al. 2023), confirming the results of the previous studies conducted in Italy. Based on these results, we developed a regionalised model for Italy, using an approach similar to that of Kotha et al. (2020) for source effects, and a zoneless approach for propagation effects. We also improved the near-source predictions, integrating the dataset with records from the NESS database (https://ness.mi.ingv.it/), and through the introduction of the explicit dependence on focal depth.

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S09c - Earthquake Ground Motion and Seismic Hazard

Non-ergodic ground-motion model for path effects due to 3-D velocity structure

DOI: 10.57757/IUGG23-4498 - LINK

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Current non-ergodic ground-motion models for path effects only capture the effects due to anelastic attenuation (δP2P_Q); however, at longer periods (T >1s), the majority of path effects is due to the 3D velocity structure. Using a Gaussian processes (GP) regression, Sung et al. (2023) found systematic path effects for T=3 sec spectral acceleration due to the 3D velocity of up to 0.5 natural log units.For modeling non-ergodic path terms using GP, a key issue is how to measure the difference between two ray paths for input into Gaussian process models. Sung et al. (2023) parameterized the path differences by the vector sum of the distance between the two source locations and the distance between two the site locations. However, this metric does not capture the main differences between ray paths pairs. We develop a new metric for measuring ray paths differences based on difference in azimuth, rupture distance, and site locations. This metric has a better physical basis, giving us more confidence in application to scenarios outside the range of empirical data. Compared to non-ergodic ground-motion models that do not include the path effect due to the 3D velocity structure, the aleatory variability is reduced from about 0.5 to 0.4 ln units. Additionally, we combine our model with efficient numerical methods (SKIP) that can accommodate large datasets with 100,000 of ground motions. Using SKIP, we can condition forward predictions of path effects at thousands of new source-site locations within a minute using traditional laptop computers with standard memory.

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S09c - Earthquake Ground Motion and Seismic Hazard

Incorporation of non-ergodic path effects into ground-motion mdels for Japan

DOI: 10.57757/IUGG23-0325 - LINK

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In current approaches for developing non-ergodic ground-motion models (GMMs), the non-ergodic path effect is through the cell-specific linear-distance scaling (Dawood & Rodriguez-Marek, 2010) that mimics the effects from a 2-D Q structure, but the significant Q effects on the ground-motion amplitudes are mainly limited to short-period ground motion at large distances. The path effects due to 3-D velocity structures are not captured by the cell-specific distance scaling approach. In this study, we adopt the new methodology from Sung et al. (2023) and Lacour et al. (2023) to estimate the spatial distribution of non-ergodic path effects using residuals from the Morikawa and Fujiwara (2013) GMM to model path effects related to 3-D velocity structures using the varying coefficient model (VCM). The epistemic uncertainty of the non-ergodic term is given by the posterior distribution in the VCM, which is small in regions with data and large in regions with spare data. The dataset is from the dense strong-motion observation networks in Japan (e.g., K-NET and KiK-net). The standard deviation of non-ergodic path terms is approximately 0.15 LN units when only considering 2-D Q path terms, whereas the standard deviation is much larger (about 0.30-0.35 LN units) if both Q and 3-D velocity structure non-ergodic terms are included. Fully non-ergodic models lead to an aleatory variance of residuals for GMMs that is reduced by 40-70% compared to ergodic GMMs. The combined effect of the shift in the median with the reduced aleatory variability can significantly affect seismic hazard calculations for the Japan region.

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S09c - Earthquake Ground Motion and Seismic Hazard

A Bayesian update of ESHM20 ground-motion model for France

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The ESHM20 ground-motion model (GMM) is developed using the pan-European Engineering Strong-Motion (ESM) dataset, and is applicable for earthquakes of 3 < Mw ≤ 7.4. This model accounts for regional variability of path and source effects via regionally adjustable anelastic attenuation and offset components, respectively, in its functional form. In low-moderate seismicity regions, such as France and Germany, events with lower Mws and paths of slower crustal attenuation could be of interest in seismic hazard assessments. For this purpose, we have performed a Bayesian update of the ESHM20 GMM using the French RESIF-RAP dataset containing ground-motion data from 2 < Mw ≤ 5.5 earthquakes. This procedure extends the GMM's applicability to smaller earthquakes and apparently slower attenuating regions of France. The updated GMM, however, predicts larger median ground-motions with a larger aleatory variability – which together would aggravate the hazard estimates in France (compared to ESHM20). Here, we present our approach, outcome, and understanding of these systemic changes in GMM coefficients and predictions following the Bayesian update. Revision of attenuation regionalisation model of France and moment-magnitude estimates of French earthquakes are in process, and may help evaluate the procedure. We anticipate that such checks and refinements would become necessary before adapting the ESHM20 GMM in seismic hazard assessments of other low-moderate seismicity regions of pan-Europe.

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S09c - Earthquake Ground Motion and Seismic Hazard

Machine Learning based Estimator for ground Shaking maps applied to the Los Angeles basin region

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Large earthquakes are among the most destructive natural phenomena. Fast estimation of the ground shaking intensities is a crucial task for hazard assessment after a large earthquake occurs.

The Machine Learning Estimator for Ground Shaking maps (MLESmap) is proposed as a novel methodology that exploits the predictive power of Machine-Learning (ML) algorithms to estimate ground acceleration values a few seconds after a large earthquake occurs. The inferred information can produce shaking maps of the ground providing quasi-real-time affectation information to help us explore uncertainties quickly and reliably.

MLESmap utilizes physics-based seismic scenarios to feed the algorithms.

Moreover, as our synthetic catalogs will never contain all possible future events, we aim at having models capable of successfully interpolating non-trained events accurately.

To set up the MLESmap technology, we used simulated ground motions from CyberShake Study 15.4, a physics-based Probabilistic Seismic Hazard model for Southern California at 1 Hz. In particular, this CyberShake study is focused on the Los Angeles basin region. Los Angeles sits on top of large sedimentary basins. These soft foundations can amplify the amount of damaging shaking these cities experience during an earthquake. Our approach (i.e. simulate, train, deploy) can help produce the next generation of ground shake maps, capturing physical information from wave propagation (directivity, topography, site effects) at the velocity of simple empirical GMPEs. In this work, we will present the MLESmap workflow and its application in the Los Angeles region as a use case.

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S09c - Earthquake Ground Motion and Seismic Hazard

Predicting time-histories using machine learning and hybrid-datasets (simulations and observations).

DOI: 10.57757/IUGG23-3106 - LINK

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Despite the continuous increase in the number of ground motion stations and the amount of recorded ground motion data in recent years, we still face observational gaps in earthquake records for large-magnitude and small-distance events. Physics-based simulations of recent earthquakes have been capable of reproducing the ground shaking recorded by near-field accelerometric stations but also predicting ground motions in other locations. In this work, we first develop a hybrid database combining calibrated ground shaking simulations and real-world observed ground motions. This hybrid dataset consists of 83864 real and near-source events records (from 1200 events) and physics-based simulations (from 20 events).

In the second step, a generative model is trained based on this hybrid dataset. The model simulates nonstationary ground-shaking recordings. It combines a conditional generative adversarial network to predict the amplitude part of the time-frequency representation (TFR) of ground-motion recordings and a phase retrieval method. This model simulates the amplitude and frequency contents of ground-motion data in the TFR as a function of earthquake moment magnitude, source-to-site distance, and a random vector called latent space. After generating the phaseless amplitude of the TFR, the phase of the TFR is estimated by minimizing all differences between the observed and reconstructed spectrograms.

The simulated accelerograms produced by the proposed method show similar characteristics to conventional ground-motion models in terms of their mean values and standard deviations for peak ground accelerations and Fourier amplitude spectral values. We finallly compare the generative model predictions with the data of the 2023 Turkey-Syria seismic sequence.

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Prediction of ground motion in South Korea based on hybrid broadband ground motion simulation

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Korea is in a stable continental region (SCR), where large earthquakes do not occur frequently. However, Korea has suffered from infrequent yet damaging earthquakes in the past. Among the instrumented earthquakes, the largest was the 2016 M5.5 Gyeongju earthquake. The 2017 M5.4 Pohang earthquake was the second largest; but it was the most damaging one, due to its proximity to urban areas, shallow hypocentral depth of 5km, and the amplification of ground motions due to the dynamic response of the Pohang basin.

Being in an SCR with a short history of instrumentation, South Korea has not collected sufficient instrumental data for data-driven ground motion models. To address this limitation, we implemented the hybrid ground motion simulation method of Graves and Pitarka (2010, 2015) to simulate earthquakes in South Korea, accounting for the crustal velocity structure and seismological characteristics of the Korean peninsula. We implemented a three-dimensional velocity model by Kim et al. (2017) and a one-dimensional velocity model by Kim et al. (2011). To model the earthquake source, we implemented Graves and Pitarka's rupture generator with a magnitude-area scaling relationship developed for SCR by Leonard (2014).

Using the implemented simulation platform, we simulated the 2016 M5.5 Gyeongju earthquake and the 2017 M5.4 Pohang earthquake and compared results with recorded ground accelerations at strong motion stations. Our study demonstrated the potential of physics-based ground motion simulation in South Korea, but it also suggested the need for further validation of the simulation method for earthquake engineering applications in South Korea.

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Ground Motion Variability from Simulation Perspective

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Ground motion variability is often left aside in the validation framework of physics-based ground motion simulation. In this study, we evaluate how the distributions of model parameters control ground-motion variability, and whether the simulations are consistent with the empirical ground-motion model in terms of both median and standard deviation.

Our analyses consist of two main steps. First, we establish a database that contains a series of simulated ground motions from a stochastic catalog (i.e., a set of earthquake scenarios consistent with the source model developed recently for the German Probabilistic Seismic Hazard map) that could occur in the Rhine Graben area. Ground-motion simulations are performed adopting the simulation method of Graves and Pitarka (2010, 2015) implemented in the Southern California Earthquake Center (SCEC) broadband platform (BBP), which we have tailored for use in the Rhine Graben. In a second step, we ablaze ground motion variability by deconstructing it into its between-event and within-event components

The analyses are performed through six different modeling assumptions reflecting various choices of stress parameters, velocity structure, site effects, and source parameters. The residual analysis through random-effect splitting captures the main components of the variability of resulting simulations. The between-event variability, for instance, is mainly controlled by stress parameter distribution at short-period and by the source parameters and slip distributions at long-period. If these distributions are well-chosen the simulations reproduce the variability of empirical models. Our results however highlight that simulations based on one-dimensional velocity models cannot reproduce the observed within-event (path-to-path) variability.

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S09d - Earthquake Ground Motion and Seismic Hazard

Statistical analysis of source, path, and site spectra of S waves recorded at the S-net sites using spectral inversion technique

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S-net is a large-scale seafloor network in the Japan Trench area, consisting of inline-type 150 observatories with seismometers and pressure gauges. We analyzed the strong-motion data recorded at the S-net sites from earthquakes with magnitudes between about 4 and 7 with focal depths lower than 70 km. To minimize the effects of nonlinear site response and weak-couplings between the seabed and sensor houses, recordings with vector peak accelerations lower than 50 gals were selected. More than 6,000 recordings with high S/N ratios from about 600 earthquakes were used. Using the spectral inversion technique, we obtained some fundamental properties of the earthquake source spectra, path attenuation, and site factors from the horizontal-component S-wave portions of the recordings. The source spectra followed the ω^{-2} source model generally well, and the estimated magnitudes were similar to the catalog magnitudes. The stress drops increased systematically with the focal depths, and the stress-drop values differed between the earthquake types. The path-averaged quality factors were somewhat larger than those in the past studies. The peak site frequencies ranged between about 0.2 and 10 Hz, while the peak amplification factors were between about 10 and 50. A moderate regionality was also observed in the distribution of site amplification factors. At some stations which were not buried, spurious site spectra were recognized. We discuss the above results and their implication in the presentation.

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Measuring nonlinear soil-behavior systematically at KiK-net sites in Japan and correlating with geological and geotechnical indicators

DOI: 10.57757/IUGG23-4095 - LINK

Karina Loviknes[1], Paolo Bergamo[2], Donat Fäh[2], Fabrice Cotton[1]
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Earthquake ground-shaking recorded at the surface is influenced by local site conditions. At stiff sites and for small ground motions, this soil response behaves linearly, at soft sites and for larger ground motions, however, the site effects starts to become nonlinear. The complex phenomena of nonlinear site-amplification remain a challenge in seismic hazard assessment, mainly because there are still few recorded observations. In this study we use the comprehensive Japanese KiK-net network to systematically capture the empirical effects of nonlinear soil response. Here the nonlinear soil-response is measured in the stations' surface-to-borehole ratios as the change in amplitude and shift in frequency between strong-motion events and the linear site-response. We then derive station-specific parameters for nonlinearity using the measurements for each station and explore the correlation between the station nonlinearity and a selection of geotechnical and geological parameters. Our results show that finding site parameters suitable for predicting nonlinear site-effects remain challenging as the nonlinear soil-behavior is largely site specific.

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S09d - Earthquake Ground Motion and Seismic Hazard

Using the predominant frequency of earthquake records as a tool to reveal nonlinear site response

DOI: 10.57757/IUGG23-1493 - LINK

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Geotechnical Engineering- Environment- Natural hazards and Earth sciences, Marne-la-Vallée, France

Nonlinear site response, which occurs when the soil strength is affected by the amplitude of the incident wavefield, is of primary interest in seismic risk assessment due to its effects in strong ground motion prediction. Nonlinear soil behavior is widely been studied mainly using laboratory experiments. However, it is still difficult to detect nonlinear site response in seismic records, in particular, in the absence of a nearby reference site. In this article, we introduce the use of the predominant frequency to characterize nonlinear effects in earthquake data recorded in Japan (KiK-net), California (DesignSafe) and Italy (ESM) regions. The principle follows the fact that nonlinear effects produce a shift of the frequency content in acceleration time histories. Traditionally, this is expected at the fundamental resonance. However, we show that the predominant frequency is more sensitive due to its higher frequency value. Moreover, the predominant frequency indicates the frequency band where a site is more responsive to the incident wavefield, which may further contribute to a higher seismic hazard. Using this method to study multiple events in seismic stations help deriving the spatial distribution of possible nonlinear effects inside a given seismic network. These observations are expected to provide much more relevance to studies of earthquake engineering and hazard analysis in the future.

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Seismic wave amplification in the foreland basin of the Himalaya from CIGN network data

DOI: 10.57757/IUGG23-0051 - LINK

Rajender Chadha[1]
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In the sediment filled foreland basin of the Himalaya data from CIGN network was analyzed to estimate seismic wave amplification using Standard Spectral Ratios (SSR) and Ratio of Source Spectrum (RSS) methods. The recordings of three largest aftershocks of M_w 7.2, 6.7 and 6.7 of the 2015 Gorkha earthquake at soft sites in the Indo Gangetic Plains (IGP) are used. Our analysis show that fundamental frequency (f_0) of the sites increase from 0.12 Hz near the foothills of Himalaya to 2.0 Hz at the southern edge of the basin and the amplification reaches about 10. But at several sites the (f_0) if difficult to select and amplification of ~5 is broadband in 0.12-0.17 Hz range. At only four sites a comparison of both the methods was possible where spectral amplifications showed both resemblance and significant differences. These differences arise because the reference spectrum in the RSS method is the geometric mean source spectrum calculated from data at many hard sites. The reference spectrum in the SSR technique, on the other hand, is obtained from the recording at a hard site located in the vicinity of the target site. Therefore, SSR method is preferable if the input motion at the target soft site is compared to a nearby hard site, otherwise in the absence of a hard site in near vicinity of a target site RSS method is more suitable as in this method ground motion can only be specified at a generic hard site that is often the case

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S09e - Earthquake Ground Motion and Seismic Hazard

Comparing recent seismic hazard models against European ground motion data: Insights, opportunities, and challenges

DOI: 10.57757/IUGG23-0547 - LINK

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[2]*Électricité de France, EDF Direction Industrielle, Aix-en-Provence, France*
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While probabilistic seismic hazard assessment (PSHA) is well-established as the principal methodology for characterizing earthquake shaking at site or across region, quantitative validation (or even simply comparison) of hazard models against recorded ground motions remains challenging. Focusing on recent models from France and Germany, alongside the 2020 European Seismic Hazard Model, we exploit the vast database of weak and strong motion observations provided by the European Integrated Data Archive (EIDA) to compare predicted and observed exceedance of shaking in regions of low-to-moderate seismicity.

EIDA vastly expands the number of records and stations available for model-to-data comparison, especially in regions of low seismicity. However, the database of usable accelerations from these stations is not a complete archive of the shaking that has occurred, even at sites in longer operation. We overcome incompleteness using observed seismicity to predict expected distributions of shaking at times and locations where gaps exist, calibrated according to inferences from the distributions of recorded motions.

With this joint observed-inferred archive we explore the opportunities for quantitative model-to-data comparison using stations from France, Germany and Italy. The analysis begins with an overview of established methods for quantitative comparison before delving further to assess the influence of non-ergodic PSHA. We also aim to relax the constraint of independence between observation sites by introducing spatial correlation into both the hazard calculation and testing metrics. This effort highlights how systematic seismic data archiving can be vital to help demonstrate the relative suitability of hazard models for application in a region.

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S09e - Earthquake Ground Motion and Seismic Hazard

Framework for Deterministic Earthquake Ground Motion Maps in Germany using Machine Learning

DOI: 10.57757/IUGG23-3261 - LINK

Andreas Steinberg[1], *Manuel Hobiger*[1], *Peter Gaebler*[1], *Hannes Vasurya-Bathke*[2], *Aida Azari Sisi*[1]
[1]*Federal Institute for Geosciences and Natural Resources BGR, Federal Seismological Survey- Nuclear-Test Ban, Hannover, Germany*
[2]*GFZ, 2.1 Physics of Earthquakes and Volcanoes, Potsdam, Germany*

The surface effects of an earthquake are typically evaluated using ground motion maps. These ground motion maps are often based on empirical ground motion prediction equations (GMPEs), which however largely neglect source physics and, therefore, the radiation pattern of seismic energy. We present a framework for evaluating seismicity in Germany in which we calculate physics-based deterministic ground motion maps based on forward modeling of full seismic waveforms for different sources; isotropic sources for smaller earthquakes and full seismic moment tensors and finite rectangular sources for larger earthquakes.

We use 1-D and 2-D Green’s function databases to rapidly consider a large number of statistically significant scenarios, including variations in Earth structure models, site effects, and source parameters. Basin effects are explicitly modelled. We apply machine learning to generate the ground motion maps even faster and incrementally improve the accuracy of our results with each earthquake based on a comparison between expected and measured peak ground velocity.

To evaluate the accuracy of our approach, we compare the ground motion predictions from our waveform simulations to those obtained from regionalized probabilistic ground motion prediction equations (GMPEs) for a variety of synthetic cases. We quantify the differences between the two approaches. We carry out specific tests for an area in southern Germany with induced earthquakes around the two geothermal power plants of Insheim and Landau in the Upper Rhine Graben. We use locally measured passive measured velocity profiles to incorporate site effects in the form of $V_{S30.}$

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S09e - Earthquake Ground Motion and Seismic Hazard

Seismicity, seismotectonics, and seismic hazard assessment for Western Mexico

DOI: 10.57757/IUGG23-0800 - LINK

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[3]National Autonomous University of Mexico, Institute of Geophysics, Mexico City, Mexico

Western Mexico is characterized by a complex seismotectonic setting, exposing the interaction among four tectonic plates. This region suffered several damaging earthquakes in the past, and subduction earthquakes occurring along the Mexican subduction zone have been also strongly felt. Consequently, this area is highly exposed to future earthquakes that may cause significant damage.

Herein, we assessed the seismic hazard in terms of PGA and SA values, for a 10% and 5% probability of exceedance in 50 years, for B, B/C and C NEHRP soil classes. To conduct such assessment, an updated earthquake catalog, as well as a focal mechanism database, were compiled for this work. In addition, two alternative seismic source models were considered in the assessment, within a logic tree scheme, each model covering the potential seismic sources in and around the studied region: shallow crustal, subduction interplate and intraplate earthquakes. The designed logic tree has also included other parameters: the Gutenberg-Richter *b*-value, the maximum expected magnitude, and the ground-motion attenuation models for the subduction seismic sources.

Concerning the most significant results, seismic hazard on the southwestern coast (parallel to the Middle America Trench) presents the highest values. For instance, the city of Lázaro Cárdenas displays mean PGA and SA (0.2 s) pair values, for a 475-year return period, equal to 0.73 and 1.60 g, 0.83 and 1.90 g, and 0.89 and 2.05 g, for B, B/C, and C site conditions, respectively. It is worth noting that the September 19 (Mw 7.7) and the September 22, 2022 (Mw 6.9) Michoacán earthquakes occurred where the highest hazard values have been obtained. Results, together with the occurrence of such large events, suggest that this assessment is accurately foreseeing the seismic hazard for one of the most active regions in Mexico.

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S09e - Earthquake Ground Motion and Seismic Hazard

Seismicity and seismic hazard assessment in West Africa

DOI: 10.57757/IUGG23-3067 - LINK

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No in-depth seismic hazard (SH) study for West Africa (WA) has ever been conducted, as the regional earthquake catalogues are incomplete. Such lack of comprehensive SH study has negatively affected planning and development of critical infrastructure and disaster risk management in WA. This study aims to bridge the knowledge gap by applying modern techniques to updating the existing catalogues and assessing the seismic hazards for the region. We updated the current catalogue for WA from International Seismological Centre, publications and data from seismic stations in WA. Different studies considered the seismotectonic setting of WA as stable continental crust and a region of shallow crustal seismicity. We investigated both schools of thought and compared results. For each scenario, three different ground-motion models (GMMs) were combined to produce each hazard map using logic tree formalism with equal weights. WA was divided into five source zones for the computation of earthquake recurrence parameters and for the entire WA region. Computed Gutenberg–Richter b-value, activity rates(λ), and regional maximum possible magnitudes(mmax) for the zones ranged from 0.84 to 1.0, 0.3–2.1, and 5.2–7.0, respectively. Calculated b-value, λ, mmax for the region were 0.77, 4.1, and 7.2. The estimated b-value (0.77) falls within generally accepted range for tectonic seismicity. SH predicted by GMMs for stable continental areas was higher than that predicted for shallow crustal seismicity. Therefore, our results confirmed that WA is characterized by a stable continental crust. The highest hazard levels were observed in parts of Ghana, Togo, Cameroon etc., ranging between 0.02g and 0.03g.

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S09e - Earthquake Ground Motion and Seismic Hazard

Underestimation of catalog-based seismic hazard analysis versus deformation-based seismic hazard analysis: A case study of Azerbaijan province, Iran

DOI: 10.57757/IUGG23-1684 - [LINK]

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[2]*International Institution of Earthquake Engineering and Seismology, Seismological Research Center, Tehran, Iran Islamic Republic of*
[3]*École Polytechnique Fédérale de Lausanne EPFL, Laboratory of Earthquake Engineering and Structural Dynamics EESD, Lausanne, Switzerland*

The Iranian Plateau is one of the most seismic regions in the world and contains several seismotectonic provinces. Azerbaijan is one of these provinces with high seismogenic potential and has experienced many earthquakes to date. Khoy M_w 5.9, [Ma1] 2023, and Ahar-Varzaghan M_w 6.4 and 6.3, 2012 double earthquakes are the most recent. Their Peak Ground Accelerations (PGA) are 0.29g, 0.43g, and 0.53g, respectively. The PGA value for Khoy is 0.35g and 0.30g for Ahar-Varzaghan, for the 10% Probability of Exceedance (PoE) in 50 years According to the Iranian design code (Standard 2800), which has a good agreement with the Khoy earthquake while it has an underestimated amount for Ahar-Varzaghan. The Iranian design code was obtained from traditional Probabilistic Seismic Hazard Analysis (PSHA) and the aim of this study is to evaluate the sufficiency of the current code represented PGAs for the case study of Azerbaijan province. For this purpose, the code amounts are compared with the results of Deformation Based Hazard Model of the Iranian Plateau (DBHM). Traditional PSHA uses the earthquakes catalogs whereas DBHM utilizes the latest Iranian combined data sets (i.e., seismicity, geodetic, and Geological data). The PGA values derived from DBHM for 10% and 2% PoE in 50 years are 0.5g and 0.82g for Khoy, and 0.38g and 0.65g for Ahar-Varzaghan, respectively, which are higher than the current design code amounts. The results show this area is prone to earthquakes with long recurrence times and higher PGA values, which not consider in the Iranian design code.

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S10a - Multi-Hazard Risk Assessment

ARISTOTLE - A multi hazard scientific expert assessment service for the EC Emergency Response Coordination Center

DOI: 10.57757/IUGG23-1226 - [LINK]

Alberto Michelini[1], *Gerhard Wotawa*[2], *Pascal Brovelli*[3], *Susan Loughlin*[4], *Nikolaos Melis*[5], *Lauro Rossi*[6], *Rocio Baro-Esteban*[7], *Giovanna Forlenza*[1], *Sara Barsotti*[8], *Paolo Fiorucci*[9], *Nikos Kallikeris*[5], *Joanna Kerr*[10], *Luca Molini*[11], *Alexandru Tiganescu*[12]
ARISTOTLE Team
[1]*Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Roma, Italy*
[2]*GeoSphere Austria, Climate and Environment, Vienna, Austria*
[3]*Meteo France, Consulting and services department, Toulouse, France*
[4]*British Geological Survey, Volcanos, Edinburgh, United Kingdom*
[5]*National Observatory of Athens, Institute of Geodynamics, Athens, Greece*
[6]*CIMA Research Foundation, Early Warning System, Savona, Italy*
[7]*GeoSphere Austria, Geophysics, Vienna, Austria*
[8]*Icelandic Met Office, Service and Research Division, Reykjavík, Iceland*
[9]*CIMA Research Foundation, Wildfire Risk Management and Forest Conservation, Savona, Italy*
[10]*UK Met Office, Global Guidance Unit, Exeter, United Kingdom*
[11]*CIMA Research Foundation, Operations Centre, Savona, Italy*
[12]*National Institute for Earth Physics, Engineering Seismology, Magurele, Romania*

This presentation describes the activities provided by the ARISTOTLE (All Risk Integrated System TOwards Transboundary hoListic Early warning, http://aristotle.ingv.it) consortium to the Emergency Response Coordination Centre (ERCC) of the European Civil Protection and Humanitarian Aid Operations Directorate (DG ECHO) for the realization of the European Natural Hazards Scientific Partnership (ENHSP). The service provided by the ARISTOTLE consortium responds to the needs of the ERCC to coordinate very rapidly the delivery of assistance to disaster-stricken countries within the EU Civil Protection Mechanism both within and outside the Union. It features a 7/24H operational system capable of assembling within a few hours relevant information on natural events that have just occurred (e.g., geo unforecastable hazards), are ongoing or that are developing (e.g., meteorological forecastable hazards). ARISTOTLE harnesses operational expertise from nationally mandated scientific institutions and agencies across Europe to provide multi-hazard, rapid assessment on natural disasters related to volcanoes, earthquakes, tsunami, severe weather, flooding and forest fires. Each hazard brings together experts to deliver a "collective analysis" which is then fed into the partnership multi-hazard discussions to provide the sought assessment. ARISTOTLE includes partner institutions from EU and non-EU Countries and from European international organizations operating in the Meteorological and Geophysical domains. They constitute the European Natural Hazards Scientific Partnership, ENHSP. This presentation describes the organization of the service in its various modes (e.g., emergency activation, routine weekly assessment, ...), its challenges and achievements, and the interaction model developed between the scientists and the ERCC disaster risk managers.

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Multi-hazard risk-informed decision-support system: A case study in Oslo, Norway

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The Alna district in Oslo, Norway is a high profile (residential, commercial and industrial) area exposed to multiple hazards, in particular to quick clay landslides. Quick clay is a marine clay sediment where the salt that binds the clay together has been washed away over time. Thus, the structure becomes unstable, and increased point loads or erosion of waterways can trigger landslides. In case of a landslide, the quick clay becomes liquefied, and major material damage and danger to life can occur. To support the authorities in selecting the optimal risk-mitigation action, this study develops the multi-criteria decision-making methodology, which accounts for the stakeholders' preferences. The Decision Support System framework includes three key steps: 1) Identify criteria for assessing the impacts of multi-hazard scenario; 2) Identify possible measures that can reduce the impacts; 3) Give objective/subjective weighting of the identified criteria, reflecting the stakeholders' preferences. The framework is demonstrated in a multi-hazard scenario (i.e., quick clay, flood and fire) of interest to the Oslo stakeholders. The impact of the considered scenario is evaluated in terms of five categories (i.e., life and health, nature and environment, economy, societal stability, and governance and control) and 13 single criteria. Through workshops with stakeholders, possible alternatives as well as the respective cost and mitigated impacts were estimated, and stakeholders' preferences were collected. The optimal action under given circumstances is identified quantitatively and is highly dependent on stakeholders' preferences. Further details of the impact analysis are needed to understand the risk landscape of different alternatives.

The Alna district in Oslo, Norway is a high profile (residential, commercial and industrial) area exposed to multiple hazards, in particular to quick clay landslides. Quick clay is a marine clay sediment where the salt that binds the clay together has been washed away over time. Thus, the structure becomes unstable, and increased point loads or erosion of waterways can trigger landslides. In case of a landslide, the quick clay becomes liquefied, and major material damage and danger to life can occur. To support the authorities in selecting the optimal risk-mitigation action, this study develops the multi-criteria decision-making methodology, which accounts for the stakeholders' preferences. The Decision Support System framework includes three key steps: 1) Identify criteria for assessing the impacts of multi-hazard scenario; 2) Identify possible measures that can reduce the impacts; 3) Give objective/subjective weighting of the identified criteria, reflecting the stakeholders' preferences. The framework is demonstrated in a multi-hazard scenario (i.e., quick clay, flood and fire) of interest to the Oslo stakeholders. The impact of the considered scenario is evaluated in terms of five categories (i.e., life and health, nature and environment, economy, societal stability, and governance and control) and 13 single criteria. Through workshops with stakeholders, possible alternatives as well as the respective

cost and mitigated impacts were estimated, and stakeholders' preferences were collected. The optimal action under given circumstances is identified quantitatively and is highly dependent on stakeholders' preferences. Further details of the impact analysis are needed to understand the risk landscape of different alternatives.

An updated exposure model for the City of Johannesburg, South Africa

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Johannesburg city is one of the most advanced commercial cities in Africa and the engine room of the South African and regional economy. It is a city with world-class infrastructure in the fields of telecommunications, transportation, water and power, and with globally-competitive health care and educational facilities. However, the city is also one of contrasts, home to both the wealthy and poor, residents and refugees, global corporations and emerging enterprises. Though, several moderate to large earthquakes have occurred throughout South Africa, yet few comprehensive exposure models exist for the country. The high population growth and rapid pace of urbanization within the City of Johannesburg (CoJ) entails a significant potential for increased economic and human losses in the event of a damaging earthquake. This study introduces a new exposure model using national datasets with a uniform approach across the municipality. The exposure model was derived with ward level statistics. This refined spatial resolution allows the model to reflect a population distribution within each ward and thereby better characterize the potential risk to earthquakes and allow identification of disaster risk hotspots. The results indicate the current concentrations of building stock in CoJ. This study provides an updated exposure model towards the probabilistic seismic risk assessment for the CoJ which involves the estimation of the probability of damage and losses resulting from potential future earthquakes. This damage and loss might occur to buildings, infrastructure, people or even the environment. The exposure model in this study covers the population, residential, commercial and industrial buildings.

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Digital platform to assess risk to natural hazards in Mexico city, Mexico

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To build disaster resilience, the National Autonomous University of Mexico and the Mexico City's Secretariat of Education, Science, Technology, and Innovation, supported a project to develop a digital platform to assess risk to natural hazards in Mexico City. This platform is based on a Geographical Information System (GIS) and its main purpose is to identify the associated risk to the following natural hazards: earthquakes, volcanic eruptions, floods, mass movement processes, forest fires, and land subsidence. Besides characterizing the local hazards for different return periods, social vulnerability was determined using thirteen indicators from data of the 2010 Mexican Census of Population and Housing. We recognize social vulnerability as those social conditions that make a community susceptible to be damaged by a hazard and it is an inherent characteristic of society. Population and critical facilities (hospitals, schools, telecommunications, etc.) were considered as exposed elements. "Social risk" is expressed using a qualitative spatial multi-criteria evaluation technique by superimposing the calculated GIS's raster of the social vulnerability over individual hazard rasters. The resulting values measure the "*likelihood of risk*". Both, vulnerability and hazard, were classified into five categories with values from 1 to 5, where 1 is low and 5 very high. As a result, we obtain a meshing array that reflects the likelihood of social risk for specific hazards. The main purpose of this tool is to provide local authorities elements for land use regulations and urban development by strengthening their prevention and mitigation actions.

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S10a - Multi-Hazard Risk Assessment

Seismic loss assessment sensitivity study based on building-specific exposure models

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Seismic exposure models are the most uncertain component in the chain of seismic loss assessments and aim to describe the built environment with information about buildings, their types and the population in them. Aggregated Exposure Models (AEM) are the most common type of exposure models, describing the built-environment in aggregates over administrative regions in which neither location nor type of individual buildings is precisely described. By combining AEMs with building parameters available from OpenStreetMap (OSM), an *open geographic database updated by volunteers*, we can improve the exposure model by providing location, occupancy type and also numbers of stories for many individual buildings, resulting potentially in a more precise characterization of buildings.

Because seismic losses highly depend on both the location and type of each building, we explore how these OSM building parameters may alter the distribution of building types and how this can accordingly affect loss assessments. We also aim to understand the impact of each building parameter on describing building types more precisely for different countries in Europe. This impact depends on the the underlying AEMs and the local/national OSM mapping activities. Both vary strongly within Europe, so that the impact on both the exposure model and the loss assessment results are country-dependent. Our preliminary results suggest that the widespread occupancy parameter helps characterizing many buildings while the not so frequent number-of-stories parameter is more capable of deciding the building type ins many countries.

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Propagating uncertainties from tsunami hazard to risk for Coquimbo Bay

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Tsunami hazard and risk analysis are examples of multi-hazard and multi-risk assessments. The procedure for probabilistic tsunami risk analysis (PTRA) involves characterization, quantification, and propagation of uncertainties from sources to the consequences. A forward and modular probabilistic framework for risk assessment, known as the PEER-type approach was originally developed for single-hazard risk assessment. However, given its practical appeal, it has also been adapted to multi-hazard and multi-risk analysis. We focus on the application of this framework for tsunami risk analysis and demonstrate how the uncertainties are going to be propagated from the hazard to the risk level. The advantage of using this approach, compared to fully simulation-based approaches for tsunami risk assessment, is that it can use already-available hazard, fragility, and consequence models. More specifically, the interval of confidence for the hazard curves can be used as a proxy for epistemic uncertainties. The procedure also considers the epistemic uncertainties in the tsunami fragility curves and the consequence functions. We demonstrate how hazard and fragility curves and their confidence intervals, and the loss models (consequence functions) can be integrated to obtain loss curves for certain locations of interest. An application of this procedure is demonstrated for PTRA for Coquimbo Bay in Chile affected by the 2015 Illapel tsunami which was a near-field tsunami generated by a subduction earthquake of 8.3 Mw rupturing a 240 km section of the Nazca–South American plate interface. We consider fragility functions already developed for mixed (masonry and wood) buildings.

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Coulomb stress transfer of the june 22nd, 1939 Accra earthquake (M=6.5) Ghana-an implication for the gravity inferred lineaments

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In view of the historically devastating earthquakes in Ghana, this study employed regional satellite gravity data to reveal the extension of the crustal network of fractures emanating from the seismically active zone in the Gulf of Guinea and its implications on Coulomb stress transfer of the June 22nd, 1939 Accra earthquake. The Accra earthquake (M=6.5), Ghana is one of the most devastating intra-plate earthquakes in sub-Sahara west African region. In order to carry out the Coulomb stress transfer study, we utilized the Fault Plane Solutions (FPS) obtained from the waveform inversion of Yarwood and Doser (1979), which revealed that the earthquake composed of two events (6.1 Mw and 6.4 Mw). This study resolved the static Coulomb Failure Stress (CFS) change onto the finite fault models of the 6.4 Mw and 6.1 Mw earthquakes and its effect on associated receiver faults. The gravity study revealed swarms of fractures emanating from the gulf of Guinea and connected with the Akwapim and Coastal boundary faults favored the enhanced CFS to generate the 6.1 Mw due to transmission of stress from the seismically

active zones in the Gulf of Guinea (boundary between the African plate and the South-American plate). The 6.4 Mw main shock was explained to correlate with release of seismic energy from the associated secondarily stressed prominent strike-slip (Akwapim) fault and strike-slip (coastal boundary fault). The direction of Coulomb stress transfer and the receiver faults of the 6.4 Mw main event have been mapped for the next big magnitude earthquake preparedness.

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Earthquake-Induced Landslide Hazard Assessment of Uttarkashi using Analytical Approach

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Earthquake has played a major role in current landslide scenario of Uttarkashi since past few decades. Moreover Uttarkashi lies in the seismically active part of India based on Indian seismic zonation map (zone IV). It has become necessary to determine the earthquake induced landslide hazard with increasing magnitude and area of earthquake. The objective of this study is to prepare an earthquake-induced landslide hazard map using Analytical Hierarchal Process (AHP) and GIS for Uttarkashi, Uttarakhand. Over 65 Earthquake epicenters (ranging from a magnitude of 3.5 to 6.8) along with landslide points in and around the study area have been considered. Further, 12 factors are taken into consideration including tectonic framework, earthquake magnitude distribution, distance to epicenter, fault/focal mechanism, topography along with other landslide factors. Shake maps are used for the peak ground acceleration (PGA) and peak ground velocity (PGV) analysis. The consistency ratio (CR) determined for AHP is 0.075(<0.1), which indicates an acceptable preference matrix for the associated factors. The weights assigned to the above factors are validated using Relative Frequency Ratio method. Earthquake induced landslide susceptibility map is prepared and the zones are classified accordingly. The validation of these maps was accomplished by the area under the curve (AUC) method.

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Testing machine learning models for building damage assessment applied to the Italian Database of Observed Damage (DaDO)

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Assessing or forecasting seismic damage to buildings is an essential issue for earthquake disaster management. In this framework, we tested six machine learning models on the DaDO database of observed damage from Italian earthquakes to assess their efficacy in characterizing seismic damage. The models included random forest, gradient boosting, and extreme gradient boosting. The input features were all or a subset of the structural features provided by DaDO, as well as macroseismic intensity. Extreme gradient boosting classification performed best, especially when using basic structural features (age, number of storeys, floor area, building height) and grouping damage according to the traffic-light-based system used, for example, during the post-disaster period (green, yellow, and red). The machine learning-based model had similar efficacy to the traditional Risk-UE method. Finally, the importance of structural features varied depending on the level of damage considered.

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S10b - Multi-Hazard Risk Assessment

Responses of a cantilever retaining wall subjected to mainshock-aftershock sequences

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A mainshock is typically followed by a train of aftershocks. Aftershocks were as strong as mainshocks in some previous cases, leading to catastrophic seismic damage by sequential excitations. Seismic designs for structures have been carried out so far based on single-ground motion. The seismic design considering earthquake sequences may be required for high seismic regions. In this study, we investigated the responses of a cantilever retaining wall under mainshock-aftershock sequences by performing finite-difference-based numerical simulations. We collect a suite of the mainshock-aftershock sequential ground motions, used as input ground motions, with a wide range of intensities from the KiK-net database, in Japan. Each mainshock-aftershock sequential motion is prepared by paring mainshock and aftershock motions recorded at the same recording station from actual earthquake sequences. It turns out that relative wall displacements developed by the mainshock-aftershock sequential motions can be much larger than those by the single mainshock motions. However, the ratio of the relative wall displacement by the aftershock motions under the sequence to that by the single aftershock motions decreases as the intensity of the aftershock motions increases. In addition, post-mainshock responses depend on the intensity of the mainshock motions. The responses by the weak mainshock motions barely affect the responses by the aftershock motions. The post-mainshock responses are pronounced with the strong mainshock motions.

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S10c - Multi-Hazard Risk Assessment

Downward counterfactual analysis as a multi-hazard risk tool

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In the historical record, disasters arising from multi-hazard events are comparatively rare. However, far more common are near-misses, where a disaster tipping-point was narrowly averted. What happened historically, is only one realization of what might have happened. Due to psychological outcome bias, people pay far less attention to near-misses than to actual losses. A downward counterfactual is a psychological term for a thought about the past, where things turned for the worse. Exploration of downward counterfactuals enhances risk awareness and can contribute to risk preparedness. There are no databases of multi-hazard near-misses, but insights can be gained from downward counterfactual analysis.

Downward counterfactual analysis is a generic risk tool, universally applicable to all types of hazard combinations. Consider earthquake fatality risk in California. Since 1950, there have been several hundred earthquake-related deaths in California. This number might have been higher by several orders of magnitude if the Lower San Fernando Dam had been overtopped on 6 February 1971. The dam was badly damaged by the M6.7 San Fernando earthquake, and if the water had been at its maximum height, as it had been the previous year, the valley would have been flooded, with massive downstream consequences. A combination of heavy rain and strong seismic ground motion might have triggered an extreme engineering disaster. This is one of a range of historical examples which will be presented from the accumulating library of multi-hazard near-misses.

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S10c - Multi-Hazard Risk Assessment

Towards Exposure-Centered Multi-Hazard Risk Assessment: A Case Study For The Adriatic

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Earthquake-induced tsunamis are relatively infrequent in the Adriatic, but their occurrence might cause substantial damages, in particular if no mitigation measures are put in place. Assessing earthquake and tsunami-induced damages and how they interact in time and space is therefore crucial in order to enhance emergency response. Damage assessment procedures are based on the knowledge of location, type and characteristics of exposed assets (namely, the exposure) and their vulnerability. Exposure datasets are commonly developed based on remote sensing products and ancillary data (e.g. census, land use), but they are often developed separately for different hazards. We discuss the role of exposure to support multi-hazard damage assessment procedures for earthquake and tsunami. The proposed approach is demonstrated considering earthquake-induced tsunami scenarios for the Adriatic, modeled based on the available active faults database and historical records. Specifically, we consider scenarios computed for the Albanian coastline and the city of Durres, which experienced a M6.5 earthquake on 26 November 2019 and a related tsunami alert (canceled later on). However, exposed assets include not only buildings and infrastructure, but also population which might dramatically increase during tourist season. We discuss the possibility of complementing exposure datasets with crowdsourced data collected by citizens. This activity would increase citizens' awareness while developing up-to-date multi-hazard exposure datasets. We present the experience of a cooperation project developed between Italy and Albania involving civil protection officers, journalists and university staff, addressing a broad range of stakeholders and supporting the development of future disaster risk reduction strategies.

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S10c - Multi-Hazard Risk Assessment

A quantitative framework for assessing physical damage and recovery dynamics from consecutive hazards

DOI: 10.57757/IUGG23-3637 - [LINK]

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Space and time play a crucial role in multi-hazard damage assessment. When two or more natural hazards occur simultaneously in the same location or within a short time frame, the physical integrity of infrastructure can be compromised, leading to two scenarios: (i) 'spatial-temporal overlapping impact', when the damage results from the combined impact of both hazards, and (ii)' overlapping spatial impact with residual and subsequent damage', in case of cumulative damage from consecutive hazards.

Current literature highlights the lack of clear frameworks for multi-hazard impact assessment. Complexity in formalising quantitative aspects and understanding feedback loops between hazard, exposure and vulnerability emphasises this gap. This research aims to develop a generalised mathematical framework for quantitatively assessing multi-hazard physical damage on exposed assets, such as buildings or critical infrastructures, over time. The proposed framework covers both cases of compound and consecutive hazards. Specifically, in the "overlapping spatial impacts with residual and subsequent damage" scenario, the framework considers the reduction in exposure value, modification of vulnerability, and recovery dynamics. A sensitivity analysis has been conducted to evaluate how the duration of recovery and its functional shape (linear, exponential, and logarithmic) affect the asset's resilience.

The framework is tested through a series of real and virtual case studies, demonstrating its applicability. Observing real scenarios allows the assessment of socioeconomic and institutional factors influencing the single and multi-hazard recovery process. By incorporating dynamic analysis into the recovery phase, we can offer decision-makers a comprehensive understanding of the impacts caused by compound and consecutive events.

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S10c - Multi-Hazard Risk Assessment

Scenario-based multi-hazard risk assessment from existing single-hazard fragility models. An application to residential building portfolios subjected to consecutive hazards

DOI: 10.57757/IUGG23-4553 - [LINK]

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[1]Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Seismic Hazard and Risk Dynamics, Potsdam, Germany
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Remarkably, the existing multi-hazard risk models that assess the physical vulnerability of exposed assets lack validation and do not offer the disaggregated effects per hazard scenario. We track that shortcoming while relying on the assumption that locally calibrated single-hazard vulnerability models available in the literature can be reused for multi-hazard risk assessment for building portfolios. This is done through a holistic method that probabilistically harmonises such single-hazard fragility models and allows us to assess the differential and cumulated damage that are expected from residential building stocks affected by cascading hazards. This is a modular approach that is composed of: (1) exposure models that classify the buildings into individual sets of classes for each hazard; (2) their spatial aggregation onto optimal geographical units whose variable resolution is compatible with the variability of the hazard intensities; (3) the probabilistic compatibilities between such sets of building classes and the damage states within their fragility models; (4) the use of state-dependent fragility functions for the second hazard. We test this methodology on the residential building stock of Lima (Peru), a coastal mega-city. Damage distributions and direct economic loss estimates are calculated for six independent mega-thrust-earthquake scenarios (main-shock) ranging from Mw 8.5 to 9.0. Thereby, the resultant distribution of damage states after the first earthquake is probabilistically converted to the reference frame of the tsunami and is later used to assess the cumulative damage using state-dependent fragility functions. This setting allows disaggregating the direct economic losses of each individual hazard to the entire cascading sequence.

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S10c - Multi-Hazard Risk Assessment

The earthquake fatality potency and load by country

DOI: 10.57757/IUGG23-0011 - LINK

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Based on our new catalogue of 2,795 fatal earthquake for the world, covering the period 856BC to March 2022 not including tsunami deaths, we estimate that the reporting of fatal earthquakes is complete for events with more than 16 fatalities since 1927. The total number of fatalities recorded is 8,336,526. 117 countries have reported at least one earthquake with one fatality or more. 77 and 52 countries have reported more than 100 and 1,000 earthquake fatalities, respectively. We introduce the ***earthquake potency*** for a country, defined as the sum of recorded fatalities divided by the number of earthquakes that it took to accumulate them, which equals the average earthquake disaster size in a given country, in units of fatalities per event. A key measure of the earthquake problem in a country is the ratio of fatalities to population size. We propose that the new parameter ***earthquake fatality load per year*** objectively measures the level of the population suffering in seismically active countries, that is, it indicates the average annual cost in lives. Ecuador, Iran, Peru, Turkey and Chile have experienced the greatest loads during the last five centuries. We suggest that in multi-hazard analyses the parameters ***potency*** and ***load*** could be introduced for floods, storms and other geohazards.

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S11a - Site Response in Urban Areas

Perspectives on the state of practice in site characterization for site response analyses

DOI: 10.57757/IUGG23-2489 - LINK

Alan Yong[1]
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I present perspectives on the use of noninvasive single- and multi-station site characterization methods and their impact on estimating site response, including the so-called double "A"s inherent within site effects phenomena: amplification and attenuation. I describe the current state of knowledge and practice using traditional independent array-based techniques through results from the 2015–2021 Consortium of Organizations for Strong Motion Observation System (COSMOS) Site Characterization Project (Yong *et al*., 2022)[1]. I also compare results for *S*-wave velocity (V_S) profiles from single-station methods—such as the earthquake horizontal-to-vertical spectral ratio (eHVSR; Nagashima *et al*., 2014)[2] technique—against those by traditional approaches (Stephenson *et al*., 2022)[3]. Through recent investigations, including results by Asten *et al*. (2022)[4], I propose optimal procedures for applying single-station and array-based methods to acquire: V_{S30}, the time-averaged V_S of the upper 30 meters, and the fundamental (f_0) and dominant (f_d) site frequencies. For V_{S30}, I show that V_{R40}, the Rayleigh-wave phase velocity at the 40 m wavelength, is suitable to estimate V_{S30} for the majority of cases encountered. Through our Wang *et al*. (2023)[5] article, I show how selections of f_0 or f_d are affected by analyst bias and propose how to address such uncertainty. Finally, I discuss the importance of measuring the site *S*-wave quality factor (Q_S) as described by our Parolai *et al*. (2022)[6] review paper, and propose methods that will advance the current practice towards a more accurate understanding of the two "A"s of site effects.

[1]https://doi.org/10.1007/s10950-022-10104-w

[2]https://doi.org/10.1785/0120130219

[3]https://doi.org/10.3133/ofr20201065)

[4]https://doi.org/10.4133/JEEG5.3.1

[5]https://doi.org/10.1785/0120210304

[6]https://doi.org/10.1007/s10950-021-10066-5

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Using single-station six-component measurements and numerical simulations for site response estimation in Munich, Germany

DOI: 10.57757/IUGG23-0349 - LINK

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Recent progress in seismic instrumentation has opened new opportunities for using wavefield gradients (strain and rotation) for several seismic applications. We show that single-station six-component (6C) measurements, combining three translational and three rotational motions, can be used to investigate the shallow velocity structure. A remarkable advantage of this single-station 6C approach is its simpler way of deployment compared to array measurements, which especially eases the application in urban areas. We performed ambient noise measurements in Munich, Germany, using an iXblue blueSeis-3A rotational motion sensor together with a Nanometrics Trillium Compact seismometer. From the 6C data we were able to compute Love and Rayleigh dispersion curves, which are inverted together with H/V spectral ratios to obtain 1D P- and S-wave velocity profiles of the upper 100 m. The resulting velocity structure is implemented with additional geological and geophysical data into a 3D subsurface model. This model is used to perform 3D seismic simulations of induced earthquakes using the spectral element code SALVUS. The simulations help to quantify the amplification effect of the shallow low velocity sediments in the Munich area. In addition, the maximum ground motion and its spatial distribution can be estimated, which is important to evaluate the seismic risk in this densely populated area.

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S11a - Site Response in Urban Areas

Comparison of near-surface attenuation estimated from seismic noise surface data and weak motion recordings in a borehole

DOI: 10.57757/IUGG23-3263 - LINK

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Within the framework of the seismic site response assessment, ambient seismic noise analyses have increasingly spread over the years, mostly to retrieve the shear-wave velocity (V_S) and the fundamental frequency of the subsoil. On the contrary, less studies focused on their potential to estimate the seismic-wave attenuation and the associated shear-wave quality factor (Q_S). Recent works conducted at a local scale proposed a linear inversion, based on a least squares algorithm, to retrieve the 1D Q_S structure of the subsurface from seismic noise measures using microarrays. This inversion requires trial-and-error tests for choosing an ad-hoc damping factor and to set a positivity constraint to the solutions. Later studies showed that the Simultaneous Algebraic Reconstruction Technique (SART) could simplify the procedure (e.g., by avoiding the introduction of a positivity constraint), still providing reliable results.
To test the capability of seismic noise for a robust estimation of the near-surface attenuation, an experiment was conducted at a test site where a 100-m-deep instrumented borehole exists. The selected site is situated in north-east Italy and is equipped with two permanent seismic sensors at 0.5m and 100m depth, respectively. Nearby the borehole, a seismic noise measurement in microarray configuration was carried out and the results were compared with those derived from the inversion of seismograms collected by the two sensors. The outcomes show a reasonable agreement, considering both the diverse spatial resolution of the techniques and the difference among the parameters estimated in the depth range where a comparison can be attempted.

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S11a - Site Response in Urban Areas

Use of machine learning to predict seismic site amplification of shallow bedrock sites

DOI: 10.57757/IUGG23-3723 - [LINK]

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[3]Professor, Civil and Environmental Engineering, Seoul, Korea Republic of

We use a number of machine learning models to predict the seismic site amplifications of shallow bedrock sites calculated from one-dimensional ground response analyses. We compare the results with a regression-based model that are conditioned on V_{S30}, site period, and peak ground acceleration. We show that use of the array type of information for the ground motion and site profile in machine learning training produces excellent predictions of the surface response. In contrast, employing parameters typically used for the site amplification models widely employed in ground motion prediction equations produces only marginal improvement compared with a regression-based model. The fit can be improved through utilization of additional parameters, although the improvement is not as dramatic as when using the array data.

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S11a - Site Response in Urban Areas

Urban Noise Tomography in Athens, Greece, using Distributed Acoustic Sensing (DAS)

DOI: 10.57757/IUGG23-3439 - [LINK]

Daniel Bowden[1], Lu Tian[1], Yuhan Wang[2], Krystyna Smolinski[1], Andreas Fichtner[1], Adonis Bogris[3], Thomas Nikas[4], Konstantinos Lentas[5], Nikolaos S. Melis[5], Christos Simos[6], Iraklis Simos[7]

[1]ETH Zurich, Department of Earth Sciences, Zurich, Switzerland
[2]University of Science and Technology of China, Geophysics, Hefei, China
[3]University of West Attica, Department of Informatics and Computer Engineering, Egaleo, Greece
[4]National and Kapodistrian University of Athens, Department of Informatics and Telecommunications, Athens, Greece
[5]National Observatory of Athens, Institute of Geodynamics, Athens, Greece
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[7]University of West Attica, Department of Electrical and Electronics Engineering, Egaleo, Greece

We use 24 km of telecommunications fiber in Athens, Greece, to explore the use of ambient noise correlations and the construction of a shallow 2D velocity model. Models of the shallow subsurface are especially important for hazard and site-response characterisation, yet traditional measurement campaigns in dense, urban environments can be challenging. Using pre-existing telecommunications fiber provides an efficient and easy way to construct such high-resolution models.

The fiber was provided by the Hellenic Telecommunications Organization (OTE), over 36 days in the Autumn of 2021, and in cooperation with the National Observatory of Athens (NOA). Using a Silixa iDAS interrogator, we measure strain-rates every 4 meters along the fiber to provide dense observations of wave propagation. Strong anthropogenic noise gives clear Rayleigh-wave signals in cross-correlations in the frequency band of 5-30 Hz. We discuss our efforts to efficiently stack multiple virtual sources' record sections and construct dispersion curves. We then invert for numerous 1D velocity profiles of the top ~100 m, comparing different approaches, and finally present a 2D model over the entire line.

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Reexamination of the subsurface velocity structure and estimation of amplification factor of Yangon, Myanmar estimated from microtremor data

DOI: 10.57757/IUGG23-4849 - LINK

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In order to understand the subsurface velocity structure of the city of Yangon, Myanmar, microtremor observations were conducted in and around the city. Data was obtained during the period of 2015 to 2018. Triangular array observations were conducted at seven locations within the study area in order to estimate the phase velocity and the velocity structure at each location. On the other hand, in order to estimate the depth distribution of the subsurface layers, single-station observation was conducted at over 150 sites to obtain Microtremor horizontal-to-vertical spectral ratios (MHVRs) (Hirokawa et al., 2016; Matsushita et al., 2018).

These data will be reinvestigated to reexamine the subsurface structure of the city of Yangon. The S-wave velocity and thickness of the layers is estimated from the phase velocity and P-wave velocity and density are estimated from the S-wave velocity using the relation by Ludwig et al. (1970). The velocity structure at singe-station observation points are estimated by fitting the observed MHVRs with the theoretical MHVRs calculated according to the diffuse field concept (Sánchez-Sesma et al., 2011) using the velocity structure estimated at the array observation locations as initial models. The S- and P-wave velocities and number of layers are fixed and only the thickness of the layers are changed to fit the data. The estimated velocity structure will be interpolated to construct a three-dimensional velocity structure and the amplification factor due to the subsurface structure is estimated.

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S11b - Site Response in Urban Areas

Local seismic zonation by cluster and correlation analysis.

DOI: 10.57757/IUGG23-5017 - [LINK]

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Site response analysis is essential for evaluating seismic hazard and risk assessment and for providing useful data for land use planning. However, current regional site amplification models do not have the necessary resolution for sites such as alpine valleys, where site response is characterized by complex effects. In this study, the site response of the lower Sarca Valley (northern Italy) was first evaluated at a limited number of sites corresponding to the locations of earthquake recordings. Then, the site response (in terms of spectral amplification curves and duration lengthening) was spatially extended where recordings of earthquakes were not available, by the application of cluster and a correlation analysis, using the noise NHV recorded throughout the valley by single-station noise measurements. In this way, could finally zonate the area into three parts with different site response characteristics: the area where the bedrock outcrops, characterized by a flat response; an area around the valley axis where the sediments reach a thickness of about 450 meters, characterized by high amplification values (up to 10) and ground motion lengthening of several tens of seconds at frequencies below 1 Hz; an area at the valley margins where the sediments become thinner, characterized by spectral amplification at frequencies between 1 and 10 Hz. The results obtained can provide useful information for hazard and risk scenarios and for improving lower resolution regional maps at the local scale.

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S11b - Site Response in Urban Areas

Set up interpolation scheme techniques to map site amplifications at local scale from seismological and geophysical data

DOI: 10.57757/IUGG23-1456 - LINK

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In the framework of the Risk Model Switzerland, Risk Model Basel and Urbasis projects, selected areas in Switzerland were used to derive local amplification models combining geological, seismological and geophysical data. The chosen sites are Visp and Sion located in the Canton of Valais in southwest Switzerland, Lucerne a densely populated city located in central Switzerland and Basel located in the northwest of Switzerland.

In the area of Visp, different amplification models are derived by means of 3D simulations and statistical correlation of horizontal-to-vertical spectral ratio and empirical amplification functions. Additionally, a further strategy for the prediction of amplification is presently being calibrated using the quarter wavelength method as a direct empirical modelling approach to estimate amplification from synthetic S-wave velocity profiles extracted from the 3D model. Instead, in the Sion, Basel and Lucerne areas beyond the statistical correlation of horizontal-to-vertical spectral ratio with empirical amplification functions as in Visp, also a method combining noise and earthquake standard spectral ratio is used.

Thanks to the available database of geophysical data and empirical amplification functions Switzerland is a good laboratory in which different techniques to map amplification can be tested and compared highlighting the advantages and limitations.

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S11b - Site Response in Urban Areas

Estimation of the seismic amplification factors from the GMMs between-station residuals

DOI: 10.57757/IUGG23-4360 - LINK

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Estimation of amplification factors (AFs) at the local or regional scale is an important task in land planning and seismic design, especially in areas with high seismic hazards and complex geological and geomorphological structures of the territory, such as Italy. When multiple seismic recordings at a single site are available, they can be exploited to estimate AFs empirically through many methods, such as: a) spectral ratios between i) the horizontal and vertical ground-motion components and ii) the shaking observed at the site and at a reference rock site, both for acceleration response and Fourier spectra; b) parametric or non-parametric generalized spectral inversion techniques; and c) decomposition of residuals of a nonergodic Ground Motion Model (Rodriguez-Marek et al., 2011; Priolo et al., 2020, among the others) to estimate repeatable within-site terms (δS2S).
In this study, we exploited the estimates of δS2S provided by Lanzano et al (2022), through the ITACA (ITalian ACcelerometric Archive) web portal (https://itaca.mi.ingv.it/ItacaNet_32/#/products/itacas2s_flatfile), to compute the AFs for about 800 recording sites in Italy. We then compare AFs estimates with different proxies for predicting the site effects, such as Vs profile, resonance frequency, cover geology and topographic slope. Moreover, we also employed the empirical AFs to validate the estimates provided by 1D, 2D and 3D numerical modeling of the site response. Later, we investigate spatial correlation of the AFs in urban areas, where dense networks are installed.

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S11b - Site Response in Urban Areas

Towards building-site-specific T–H relationships: The FRIBAS database

DOI: 10.57757/IUGG23-1918 - [LINK]

Bojana Petrovic[1], Maria Rosaria Gallipoli[2], Giuseppe Calamita[2], Nicola Tragni[2], Chiara Scaini[1], Carla Barnaba[1], Marco Vona[3], Stefano Parolai[4]
[1]National Institute of Oceanography and Applied Geophysics - OGS, Center for Seismological Research - CRS, Sgonico TS, Italy
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Site response in urban areas is influenced by the presence of buildings and their interactions with the soil. The simplified dynamic response of buildings, and especially their fundamental period of vibration, can be determined by empirical characterization. However, a large variability is observed between buildings located at different sites, even if they belong to the same building typology. Our study focuses on the impact of the main characteristics of buildings (i.e., the construction materials) and soil (i.e., rigid or soft), and thus soil-structure interaction, on the structural response of buildings. For this purpose, the main characteristics of 312 buildings (constructed of reinforced concrete, unreinforced masonry or mixed materials) and their associated foundation soils were collected from different surveys in southern and northern Italy and published in an open-access database called FRIBAS (https://doi.org/10.5281/zenodo.6505442). It contains a total of 37 parameters, such as different structural and geometrical characteristics of the building (e.g., construction material, number of floors, shape) and soil properties (e.g., outcropping geology). Moreover, the fundamental vibration periods of the buildings and soil were estimated using the Horizontal-to-Vertical spectral ratio from ambient vibration measurements. FRIBAS gave us the opportunity to investigate the influence of construction materials and soil types on building periods. Our results suggest that a general T-H relationship is not sufficient, but that it is necessary to develop building-site-specific T-H relationships. FRIBAS is a fully public database that allows the entire scientific community to analyze the influence of various building and soil properties on the dynamic behavior of buildings.

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S12a - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Insights into Subduction Zone coupling from the 2020 - 2021 Alaska (Shumagin) earthquake sequence

DOI: 10.57757/IUGG23-1254 - LINK

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Prior to July 2020, the Alaska-Aleutian subduction zone near the Shumagin Islands had not experienced a large, Mw7.0+ earthquake in over 75 years. The previous major events in this region were the great (Mw8.0+) 1938 and 1946 earthquakes. These events occurred on either side of the “Shumagin Seismic Gap”, a region that has not hosted a great megathrust earthquake in recorded history. Attention to this region was renewed with the occurrence of three large earthquakes: the 22 July 2020 Mw7.8 Simeonof megathrust event, the 17 October 2020 Mw 7.6 Sand Point intraslab (strike-slip) event, and the 29 July 2021 Mw8.2 Chignik megathrust event. The two 2020 events and subsequent aftershock activity were shown to be consistent with a transition from high plate interface coupling east of the Shumagin Gap to a generally uncoupled megathrust in the Shumagin Gap. The 2021 Chignik earthquake was located in a section of the subduction zone that hosted previous large earthquakes and that was brought closer to failure by the seismicity of the previous year. Analyses of the Chignik earthquake sequence and the previous large earthquakes provide additional constraints on the transition from coupled to uncoupled along the Aleutian megathrust and implications for earthquake processes. In particular, the evolution of events in this sequence is compatible with occurring in the stress field produced by the coupling transition, which also allowed more complete elastic strain release during the large earthquakes.

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S12a - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Characterizing the foreshock, main shock, and aftershock sequences of the recent major earthquakes in Southern Alaska

DOI: 10.57757/IUGG23-1885 - LINK

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[3]*Pushkov Institute of Terrestrial Magnetism- Ionosphere and Radio Wave Propagation- Russian Academy of Sciences IZMIRAN, Wave propagation, Troitsk, Russian Federation*
[4]*Institute of Earthquake Prediction Theory and Mathematical Geophysics- Russian Academy of Sciences, Seismic data analysis, Moscow, Russian Federation*
[5]*Gubkin Russian State University of Oil and Gas, Seismic data analysis, Moscow, Russian Federation*

We continue analysing earthquake sequences in terms of their variability and scaling properties, including the behaviour of the control parameter η of the unified scaling law for earthquakes (USLE), along with a detailed analysis of the surface wave records for reconstruction of the source in approximation of the second moments of the stress glut tensor to obtain integral estimation of its length, orientation, and seismic process development over time. In particular, we present the analysis of the cases of the three recent earthquakes in Southern Alaska – 22 July 2020, Mw7.8 at 105 km SSE of Perryville, 19 October 2020, Mw7.6 at 97 km SSE of Sand Point, and 29 July 2021, Mw8.2 at 99 km SE of Perryville – that have occurred right at the western edge of the rupture zone of the 1964 Great Alaska, M9.3 mega-earthquake and contribute to apparent activation of the region started with the three major earthquakes (24 January 2016, Mw7.1, 23January 2018, Mw7.9, and 30 November 2018, Mw7.1) at its north-western and southern borders.

Due to yet rather small number of case studies, it seems premature to discuss if the observed quantitative characteristics of seismic variability and their scaling properties disclose clear patterns useful in operational earthquake forecasting of seismic catastrophes including the extreme mega-earthquakes. However, our studies give a new insight into better understanding of seismic dynamics in the Pacific Northeast.

The study is carried on in the framework of the Russian State Task of Scientific Research Works of IEPT RAS (0143-2019-0006, 0143-2019-0007).

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Historical earthquakes, rupture zones and the earthquake cycle along the East Anatolian Fault

DOI: 10.57757/IUGG23-4114 - LINK

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The region of the East Anatolian Fault (EAF) experienced several strong earthquakes during the instrumental period of seismology, i.e. after AD 1900. However, the devastating earthquake (Mw7.8) of 6 February 2023, that ruptured along the EAF, is the first to occur with such a large magnitude in that time interval. Then, some questions of fundamental importance for the earthquake cycle in the EAF raise. When earthquakes of similarly large magnitudes occurred in the past? Which segments of the EAF ruptured? What is the mean repeat time of the large EAF earthquakes? To respond to such challenging issues we organized a data base of historical earthquakes that caused significant damage in the region of EAF and assigned macroseismic intensities in terms of MMI scale. Earthquake magnitudes were calculated from empirical magnitude/intensity relationships. Mapping of lateral rupture zones along the EAF was based on higher degree isoseismal curves (e.g. degree VIII) and on evidence of surface-fault traces and other ground failures. Preliminary results showed that rupture zones of the large magnitude earthquakes abut and do not overlap, while the repeat times are of the order of several hundred years.

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S12a - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

The ISC Seismic Event Bibliography: An asset for studying recent earthquakes

DOI: 10.57757/IUGG23-0475 - LINK

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Since its launch in 2014 (Di Giacomo *et al.*, 2014), the International Seismological Centre (ISC, www.isc.ac.uk) Seismic Event Bibliography service has been very popular with researchers worldwide. Indeed, this service differs from other literature search engines since it is based on the association between seismic events in the ISC Bulletin and bibliographic records. As such, web searches (www.isc.ac.uk/event_bibliography/bibsearch.php) are not only based on bibliographic parameters (e.g., author, journal title, year of publication) but also on event parameters (e.g., origin time, location). In addition, the literature considered is not limited to seismology but includes a broad range of disciplines (e.g., earthquake engineering, geodesy and remote sensing, tectonophysics and volcano-tectonics, monitoring research, tsunami, landslides, geology, geochemistry, hydrogeology, atmospheric sciences), a feature that makes the service useful also for multidisciplinary studies. Hence, the ISC Seismic Event Bibliography is an asset both to researchers studying specific events as well as editors and reviewers during every stage of the publication process.

The bibliographic record of this service has grown significantly in recent years, and new papers related to recent significant earthquakes (e.g., May 21, 2021, Maduo; 29 July, 2021, Chignik; 6 February, 2023, East Anatolian) as well as other types of seismic sources (e.g., the 15 January 2022 Hunga Tonga Hunga Haapai eruption) are published at increasing speed. In such a context, with this contribution we aim to showcase the usefulness of the ISC Seismic Event Bibliography, how the community can use it best and, at the same time, help improve it and facilitate its maintenance.

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Analysis on the seismogenic structure of the 5 September 2022 Ms6.8 Sichuan Luding earthquake sequence, China

DOI: 10.57757/IUGG23-1377 - LINK

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On September 5, 2022, an *M*s6.8 earthquake hit the Luding County in Sichuan Province, China, and caused 93 deaths and 24 people missing. The spatial distribution of the relocated Luding earthquake sequence reveals an NNW-trending aftershock zone with long axis about 55 km along Moxi segment, the southern segment of Xianshuihe fault zone (XSH). The aftershock zone is wider in the middle and narrower in the southern and northern sections. The *M*s6.8/*M*w6.44 mainshock with centroid depth at 3.0 km and the two *M*s≥5.0 aftershocks occurred in the middle section. The strike, dip and rake angles of the nodal planes I and II of the focal mechanism for the mainshock are 75°/90°/155° and 165°/65°/0°, respectively. The areal strains *A*s exhibit a pure strike-slip faulting style both for the mainshock and the aftershocks in the southern and northern parts, while the aftershocks in the middle section are of pure or oblique extensional. Based on the spatial distribution of aftershocks, the focal mechanism solutions of the entire sequence and the structural trending in the aftershock zone, we conclude that the seismogenic fault of the *M*s6.8 Luding earthquake is the NNW-trending Moxi fault on the southern segment of XSH. The seven *M*s≥3.1 aftershocks in the middle section of the aftershock zone and the four *M*s≥3.4 events in the 2016 Luding earthquake swarm with pure or oblique extensional behaviors imply the possible existence of a series of SSE (NNW)-striking normal faults, some of which might contribute to the occurrence of aftershocks there.

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Role of Poroelasticity and Viscoelasticity during the Postseismic Deformation of the 2021 Mw 7.4 Maduo, China, Earthquake

DOI: 10.57757/IUGG23-1318 - LINK

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[2]*China University of Geosciences Wuhan, School of Geography and Information Engineering, Wuhan, China*

The 2021 M_w 7.4 Maduo earthquake that occurred within the Bayan Har block provides us with a unique opportunity to understand the lithospheric mechanical properties in northeastern Tibet. We retrieve the coseismic displacements and time series of postseismic deformation associated with the Maduo earthquake from Sentinel-1 InSAR data. We estimate the detailed coseismic slip distribution from the coseismic deformation fields and analyze possible postseismic processes by modeling the six-month postseismic deformation. The coseismic rupture is dominated by sinistral strike-slip motion and concentrated at 0-15 km depth with a peak of ~4 m. Our optimal afterslip-poro-viscoelastic model is not only physically more reasonable, but also has the best data fit. The postseismic deformation is dominated by afterslip located at depths of 10-20 km, revealing a complementary pattern with the updip high coseismic slip. Yet ignoring poroelasticity and viscoelasticity will result in errors in the afterslip of >12 cm locally. Poroelastic rebound contributes significant postseismic LOS deformation, up to ~14 mm, near the northwest and southeast fault segments. The steady-state viscosities in the lower crust and upper mantle are 4×10^{19} Pa·s and 2×10^{20} Pa·s, respectively, agreeing with the “Jelly Sandwich” model, but not with the crustal-flow models featuring much lower viscosity.

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Velocity contrast along the rupture zone of the 2022 Mw6.8 Luding, China, earthquake with fault zone head wave

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Fault zone head waves (FZHWs) are an essential diagnostic signal which can provide high-resolution imaging of fault interface properties at seismogenic depth. In this study, we investigate the existence of bi-material interfaces along the rupture zone of the 2022 Mw6.8 Luding earthquake at the southern Xianshuihe Fault and determine the cross-fault velocity contrast. We employ a semi-automatic workflow to detect FZHWs and the direct-P waves. We improve the identification ability of potential FZHWs in the automatic picking process with a combination of STA/LTA functions and a kurtosis detector in a “forward-detecting and backward-picking” strategy. We confirm 206 FZHWs at two stations. Results indicate average velocity contrasts of ~5 % along the northern segment of the rupture zone while it decreases to ~3% in the south, with the northeast side having a faster P-wave velocity, in agreement with tomographic results. We also noticed that some direct-P waves do not polarize parallel to the back azimuth, indicating a complex site effect beneath the station. The distribution of FZHW-generated events indicates the existence of a single continuous interface in the seismogenic zone with length about 100km, which might be conducive to the preparation of large earthquakes and further influence the dynamic rupture processes. The velocity contrast across the rupture zone indicates a statistically preferred NW propagation direction for typical subshear ruptures. However, the rupture direction of the Mw6.8 Luding earthquake was primarily from NW to SE, suggesting that other factors, such as heterogeneous stress distribution along the fault, might impact the rupturing direction.

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S12b - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Joshimath landslides and subsidence 2023 in Uttarakhand Himalaya: A critical geological analysis and a lesson for sustainable development

DOI: 10.57757/IUGG23-1269 - LINK

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The tourist town of Joshimath in the west of Indian Himalayas, is bounded by NNW-SSE Munsiari Thrust in the north and Main Central Thrust Faults in the south. The study of tectonic structural configuration indicates that these two faults caused differential fragmentation of Joshimath slab. Like many other parts of a young mountain building system, the town is prone to various types of landslides, subsidence, slope failures, avalanches, debris and mud flows. The surface geological materials are composed of heterogeneous piedmont deposits in northern slope of the mountain facet, consisting of weathered boulders of gneisses and schistose rocks amalgamated with silty-sandy matrix. This study finds that the Alakananda River strongly smack the north-east foothill of Joshimath cliff from the north and cause severe scour, erosion of the ground and infiltration of running water before merging into a structurally controlled vertical gorge. The remaining volume of water is carried out by Dhauliganga river. The existence of number of active NS trending short gravitational (Normal) faults and deep fractures in the east and west side of the Joshimath town, caused northward slip of the Joshimath slab. Our mathematical modelling suggest that tensile stresses generated in compressive thrust wedge under low friction on boundary thrust of wedge causes shallow subsidence. Unplanned construction activities and inconsistent modification of natural topography add on to the impact of natural degradation and damages urban structures. A planned urban construction consistent with geological and geomorphological environment and aligned to the seismic and meteorological conditions is recommended in Himalayas.

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S12b - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Newly discovered faults in Indonesia revealed by recent destructive earthquakes

DOI: 10.57757/IUGG23-0610 - LINK

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Indonesia is one of the most earthquake-prone countries in the world. Its highly complex tectonics setting is the result of collision between the Australian and Sunda blocks, and the interaction of the Pacific and Philippine Sea plates. Prior to 2017, the National Center for Earthquake Studies of Indonesia database recognised 295 active faults throughout Indonesia. The additional seismic stations operated by the Agency for Meteorology, Climatology, and Geophysics over the past 5 years has greatly improved the detection of small earthquakes from previously unidentified faults. In this study, we investigate recent destructive earthquake sequences in Indonesia along with their associated foreshock and aftershocks. We find, using a variety of techniques including relative relocation of hypocenters, focal mechanism determination, and Coulomb stress modelling, that the main shocks occurred on previously unknown faults, including the Majene Fault in West Sulawesi, the Kalaotoa Fault in the Flores Sea, a small graben system in Semangko Bay (Southern Sumatra), the Kajai Fault in Pasaman (West Sumatra), and a conjugate fault in Cianjur (West Java). Mapping these active faults is very important for updating seismic hazard maps and understanding their implications. The Turkey earthquake on February 6, 2023, serves as a reminder that shallow crustal earthquakes caused by active terrestrial faults located near large population centers pose a major natural hazard.

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S12c - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Diverse Rupture Characteristics between the 2023 Mw 7.8 and Mw 7.5 Turkey Earthquakes

DOI: 10.57757/IUGG23-5013 - LINK

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[5]Université de Strasbourg/CNRS, Institut Terre et Environnement Strasbourg, Strasbourg, France
[6]University of California Santa Cruz, Department of Earth and Planetary Sciences, Santa Cruz, USA

On 6 February 2023, an M_W 7.8 earthquake occurred on the southwestern part of the East Anatolian Fault zone (EAF), followed by an M_W 7.5 at ~100 km away on the East-West striking Sürgü fault 9 hours later. The W-Phase inversions indicate major strike-slip with dip angles of 60° for both events. A notable difference in seismic waveforms between two major earthquakes suggests different rupture characteristics. High-frequency back projection images for the M_W 7.8 event from the dense broadband ChinArray shows a NE unilateral rupture from the onset for 40 sec with the expansion to the EAF trace since ~20 s and stopping at the junction of EAF and Sürgü fault, along with some late radiation at ~40-60 s to SW at the Amanos segment of EAF. The back projection image for the M_W 7.5 event shows a main high-frequency coherent energy release for the first 10 sec over ~40 km and late weak radiations to the west near the curved Cardak fault and to the east near the Malatya fault. Preliminary slip models inverted from teleseismic data indicate a complex rupture for the M_W 7.8 event predominantly on the EAF and a localized slip for the M_W 7.5 event. The difference also exhibits in body-wave magnitude with m_B=7.5 for the M_W 7.5 and m_B=7.2 for the M_W 7.8 events. We are exploring InSAR images, hr-GNSS, and strong-motion data to constrain details in the rupture process of both events.

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Rupture processes of the 2023 Türkiye earthquake sequence: Main- and aftershocks

DOI: 10.57757/IUGG23-3247 - LINK

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On February 6, 2023, southeastern Turkey was hit by two of the most devastating earthquakes in the instrumental period of the country, with Mw 7.8 and Mw 7.5, respectively. Both earthquakes caused massive damage in Turkey and Syria. In this study, we analyze the rupture processes of main- and aftershocks by combining different seismic source characterization techniques using teleseismic, regional, and local data. We perform finite source inversion and back projection-based analyses for the two main shocks and invert for probabilistic centroid moment tensor solutions of both main and aftershocks (M≥4). The first earthquake was bilateral and ruptured a seismic gap along the East Anatolian Fault, with rupture first propagating to the north-east for ~200 km, and in a latter phase propagating to the SSW, probably coming to a halt only on a branch extending into the Mediterranean Sea. The total length of the rupture likely exceeds 500 km. The second event ruptured the EW-oriented Sürgü-Misis Fault to the NW of the first event. It shows a highly concentrated rupture near the epicenter, Rupture directivity analyses for M≥5.3 earthquakes provide additional insights into dynamic source aspects. Preliminary moment tensor solutions of numerous aftershocks indicate a remarkable variability of rupturing mechanisms, suggesting stress changes and the activation of multiple faults in the vicinity of the main ruptures. With our work, we aim to shed light onto multiple aspects of the complex rupture evolution and hope to provide new insights towards a better understanding of the devastating 2023 Türkiye earthquake sequence.

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S12c - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

The complex initial rupture of the 2023 Mw 7.8 earthquake in Turkey

DOI: 10.57757/IUGG23-4822 - [LINK]

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Two earthquakes struck eastern Turkey and caused severe damage on 6th February 2023. The magnitudes are Mw7.8 and Mw7.7, respectively. The rupture processes of the two earthquakes are significantly different. The Mw7.8 earthquake has a gradual initial rupture, resulting in a longer duration time. In addition, the epicenter is located at a small branch.

We focus on the initial rupture constrained by teleseismic data. We set up fault planes based on preliminary online geodetic and seismology results by other researchers. After a series of tests, we could not simulate the initial rupture well based on the uniform sub-fault size (6x4km).

We carry out a two-step inversion strategy. Firstly, we used a rectangle fault with a length of 26km and a width of 30km to simulate the first 12s teleseismic P waveforms. The sub-fault size is 2x2km. The strike and dip angles are 220° and 70°, respectively. The residual teleseismic waveforms between synthetic and the whole observed teleseismic waveforms are calculated.

Secondly, Two rectangle segments with larger sub-fault sizes and different strike angles (220° and 235°) are applied to simulate the residual teleseismic waveforms. The sub-fault size is 6x4km.

The result indicates that the initial rupture propagated downward along the dip-slip direction which is a nearly pure strike-slip event. The moment is 1.3x10^19 Nm, and the corresponding moment magnitude is Mw6.7, about 2% of the total moment.

A significant normal component could be observed at the shallow depth between the initial pure strike-slip patch and the body patch, which is consistent with the tectonic background.

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Analysis of the ground motions and felt intensity during the February 6 earthquakes in Southeastern Turkey

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On February 6, 2023, two large earthquakes with moment magnitudes of 7.8 and 7.5 occurred in Southeastern Turkey. These two earthquakes caused significant damage and a high number of fatalities in the provinces of Kahramanmaras, Hatay, Adiyaman, Osmaniye, Gaziantep, Kilis, Sanliurfa, Diyarbakir, Malatya, Adana, and Elazig. A dense array of seismograms close to the fault ruptures recorded both earthquakes. Some of these records are observed to have very large amplitudes with peak ground acceleration values over 1 g and peak ground velocity values over 150 cm/s. This study provides a detailed analysis of the recorded ground motions and investigates potential reasons behind the significant structural damage and observed extreme motions with very high amplitudes. These reasons include multi-segment fault ruptures, multiple high-amplitude wave packets observed in the records, rupture directivity effects, and the occurrence of strong velocity pulses. The recorded ground motions are also compared to the current and previous seismic codes of Turkey for various return periods. Next, shaking intensities in terms of the Modified Mercalli Intensity (MMI) scale are estimated using empirical models which relate peak ground motion parameters to the felt intensity. These estimates are then compared to the reported intensity values from field observations. Discrepancies between the estimated and reported intensity values are investigated.

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S12c - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Near source adjustment factors versus 2023 Turkish strong-motion records

DOI: 10.57757/IUGG23-4386 - LINK

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Within the proximity of the source of medium-to-large earthquakes, seismic ground motion exhibits peculiar characteristics that can hardly be reproduced by global and regional empirical models (GMMs), usually adopted for hazard assessments and shaking scenarios.

High amplitudes (in terms of peak values and spectral ordinates), velocity pulses, vertical motions greater than their horizontal counterparts, and permanent displacements are some of the characteristics observed during strong worldwide earthquakes.

The paucity of near source observables does not allow the calibration of robust empirical models for their prediction, and to overcome this limitation, adjustment factors have recently been calibrated to be applied to classical GMMs for several ground motion parameters using the NESS recording dataset.

The recent earthquake sequence in Turkey produced a large amount of near source recordings close to the different activated fault segments, which provide an opportunity on the one hand to validate the previously calibrated adjustment factors and on the other hand to investigate the characteristics of additional shaking parameters related to energy content and release mode, such as waveform envelopes, arias intensity and duration.

Keywords: Turkish event, ground motion models, near source features and intensity measures.

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S12d - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

The 2023 Kahramanmaras (Turkey) earthquake sequence (Mw 7.8, 7.6): Coseismic and interseismic results from Active faulting, InSAR and GPS

DOI: 10.57757/IUGG23-4846 - [LINK]

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[2]Istanbul Technical University, Maaden Facultesi, Istanbul, Turkey
[3]Osmangazi University, Dept of Geology, Eskisehir, Turkey
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[6]Yildiz Technical University, Faculty Of Civil Engineering, Istanbul, Turkey

An earthquake sequence occurred along the East Anatolian fault (EAF, Mw 7.8) and Sürgü fault (SF, Mw 7.6) in the Kahramanmaras region (Southern Turkey). Both earthquakes show strike-slip mechanisms and shallow hypocentre (<15 km), with NE-SW trending Kahramanmaras and Karasu fault segments reaching ~300 km and E-W trending 150 km Sürgü fault length, respectively. An analogue seismic event according to historical catalogue is the 29 November 1114 that severely affected Antachia, Marash and Urfa with about 40 000 victims. Christian and Muslim chroniclers report the occurrence of two large seismic events, a comparable situation to the 2023 events. Field investigations conducted in 2005 in the frame of the EC-Funded APAME project show ~4 m to ~80 m left-lateral offset streams along the fault zone south of Kahramanmaras city. InSAR results from Sentinel images provide an accurate mapping of the Kahramanmaras and Karasu fault traces with estimated ~3 m to ~8 m left-lateral slip along strike. Repeated GPS measurements from 1991 – 2004 allow us to determine horizontal velocities of 22 stations located across the EAF in southern Turkey. By using a simple locked fault model, we estimate that the relative left-lateral plate motion across the EAF is 9.7 ± 0.9 mm/yr., and 4.4 ± 0.4 mm/yr across the Karasu fault. The ~900 year of interseismic relative quiescence and 9.7 mm/yr left-lateral block velocity, surface faulting geomorphology and paleoseismic results along the EAF may explain the occurrence of the Mw 7.8 event.

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S12d - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Fault slip distribution in the February 2023 Kahramanmaraş earthquake sequence from Sentinel-1 and ALOS-2 image offsets

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The 6 February 2023 Kahramanmaraş earthquake sequence involved two major earthquakes (M7.8 and M7.5) within 12 hours on separate faults, causing widespread damage and loss of life in SE Turkey and NW Syria. Dense image offsets, computed from Sentinel-1 and ALOS-2 SAR images, provide robust measurements of the surface deformation of both events; I use them here to estimate the distributions of slip on their causative faults.

I use the ISCE software to produce both range and azimuth offsets, for multiple ascending and descending tracks, and use them to map the major fault traces and splay faults involved in the earthquakes. To downsample the offsets into a useable form for modelling, I first use a distance-based sampling approach to produce a preliminary model, and then use a quadtree decomposition based on the modelled displacements to sample the offsets, employing a median filter to reduce the influence of noise originating from false image matches. Finally, I use the Okada-based slipinv software to invert for the slip distribution.

Preliminary results show a heterogeneous pattern, with up to 8 m of slip on a ~250 km rupture of the East Anatolian Fault (EAF) corresponding to the first event, and a ~125 km rupture of the Sürgü Fault, peaking at 9 m of slip, to the second. Both faults have splays that highlight possible complexities of both events, including a splay that likely initiated the first event, connecting to the centre of the main asperity on the EAF.

The 6 February 2023 Kahramanmaraş earthquake sequence involved two major earthquakes (M7.8 and M7.5) within 12 hours on separate faults, causing widespread damage and loss of life in SE Turkey and NW Syria. Dense image offsets, computed from Sentinel-1 and ALOS-2 SAR images, provide robust measurements of the surface deformation of both events; I use them here to estimate the distributions of slip on their causative faults.

I use the ISCE software to produce both range and azimuth offsets, for multiple ascending and descending tracks, and use them to map the major fault traces and splay faults involved in the earthquakes. To downsample the offsets into a useable form for modelling, I first use a distance-based sampling approach to produce a preliminary model, and then use a quadtree decomposition based on the modelled displacements to sample the offsets, employing a median filter to reduce the influence of noise originating from false image matches. Finally, I use the Okada-based slipinv software to invert for the slip distribution.

Preliminary results show a heterogeneous pattern, with up to 8 m of slip on a ~250 km rupture of the East Anatolian Fault (EAF) corresponding to the first event, and a ~125 km rupture of the Sürgü Fault, peaking at 9 m of slip, to the second. Both faults have splays that highlight

possible complexities of both events, including a splay that likely initiated the first event, connecting to the centre of the main asperity on the EAF.

S12d - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Unique insight into the Feb 6 2023 Turkiye earthquake sequence from GNSS geodesy

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The February 6 2023 earthquake sequence in the East Anatolian Fault Zone (EAFZ) was dominated by events of magnitudes (Mw) 7.8, 6.7, 7.5, and 6.0 within an 11-hour window. The EAFZ falls within the CORS-Tr, the Turkish national network of 167 GNSS stations with a spacing of 80-100 km, delivering carrier phase data every 1 s. This dense network allows us to estimate the displacement field during this devastating earthquake sequence with unique spatio-temporal resolution and precision. This presents the opportunity to understand this sequence in ways that are uniquely enabled by GNSS: (1) CORS-Tr data started in 2008 which, together with global data, provides a long-term context on plate rotations, interseismic strain accumulation, co-seismic strain release, and post-seismic relaxation. (2) GNSS effectively extends the temporal sensitivity of seismology from seconds to decades, enabling detection of aseismic deformation that is not associated with the seismic radiation field. (3) In contrast to InSAR, GNSS provides temporal resolution between the events, and unambiguously samples displacements in 3 dimensions. Given these unique capabilities, scientific interpretation can be strongly enhanced by considering the GNSS data together with data from seismology and geodetic imaging techniques such as InSAR, pixel tracking, and optical methods. Here we present results that highlight the strengths of the CORS-Tr GNSS data for constraining all aspects of the seismic cycle, including pre-seismic strain accumulation, the permanent co-seismic displacement field including far-field motions that are sensitive to the deepest part of slip, post-seismic relaxation, and aseismic moment release in between episodic events.

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S12d - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

AgLoc: Acoustic-GNSS Location Methods for Earthquake First Responders

DOI: 10.57757/IUGG23-5011 - LINK

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Recent Earthquakes happening in Turkey can have devastating impacts on human communities, while the ability to locate missing persons quickly is crucial to reducing the death toll. However, this task can be challenging when earthquake victims are sparsely distributed in large, GNSS-blocked fields. In this paper, we propose a solution that combines GNSS and acoustic signals to accurately locate missing persons in earthquake ruins. Requiring no infrastructures, our method utilizes accurate acoustic ranging to compensate for the loss of the GNSS carrier phase to achieve higher localization accuracy, especially in complex half-blocked environments or in areas where GNSS signals are weak or even unavailable. The proposed method is not only effective but also shows unparalleled compatibility, making it widely applicable in various disaster response scenarios. Offering a flexible and versatile way of signal combination, AgLoc can be easily compatible with different types of end-equipment, dedicated to providing a solution that enables high-precision localization of first responders and survivors.

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S12d - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Rapid and high-resolution damage proxy maps from space observations combined with building data from volunteer mapping

DOI: 10.57757/IUGG23-4185 - LINK

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After large damaging earthquakes, fast and well-informed help efforts can save lives. The key information are the location and extent of damage and losses, in particular for disasters that affect large areas. Space-borne imaging methods, together with building-wise exposure data, can enable rapid damage assessments, delivering damage proxy maps for an entire affected region within hours.
Space-borne damage proxy maps are generated e.g. from repeated synthetic aperture radar (SAR) imaging of the ground before and after an event to detect changes in the radar backscatter. Such changes are expressed in a drop of interferometric (InSAR) coherence. Dense human infrastructure, like building agglomerations, shows long-term stable backscatter characteristics and high coherence compared to many natural surfaces. Therefore, a sudden drop in coherence between pre- and post-earthquake images can be attributed to damage on the ground. However, without further information a detected damage tells little about the involved severity concerning human lives. Also, less dense settlement structures like villages may not show as long-term coherent areas and may not be included in damage maps even if strongly affected.
Based on InSAR damage proxy maps from the 2023 Turkey Syria earthquakes, we present an approach to augment InSAR damage maps with information from exposure models combined with open building data. This combination can improve guiding rescue efforts by highlighting approximated damage with exposure models. Also, the building data help revealing blind spots in damage proxy maps, which are method-related, and should not go unnoticed.

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S12d - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Seismicity before and after the 2023 M7.8 and M7.5 earthquake sequence in Turkey: A preliminary report

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We provide a preliminary report on seismicity before and after the 2023 *M*7.8 and *M*7.5 earthquake sequence.

One feature for seismicity during 2013-2022 was the 2020 *M*6.8 earthquake (data from KOERI-RETMC, in Bogazici University). Aftershocks since the *M*6.8 earthquake suggest that the south end of the *M*6.8 rupture was close to the north end of the *M*7.8 rupture. Another feature is a seismic swarm on and around the fault segment, from which the *M*7.8 rupture was initiated. On this segment, an area of large slip (~1.3 m) was overlapped with this swarm. Since late 2022, this swarm was activated, with a clear decrease in the Gutenberg-Richter *b*-value to *b*=0.7~0.8, indicative of an increase in stress. In-depth analyses to verify whether the *b*-value in the large-slip area pronouncedly decreased preceding its occurrence need to be performed, as in the case for the 2011 *M*9 Tohoku-oki earthquake in Japan (Nanjo et al., 2011).

Comparing with the stress imparted by the *M*7.8 and *M*7.5 earthquakes (Toda et al., 2011, 2023), we noted the lack of post-*M*7.5-quake seismicity at the zone of increase in stress beyond the north end of the *M*7.8 rupture and that this area lacking in seismicity closely matched to the area of the *M*6.8 rupture. Future activation that extends to the north on the East Anatolian Fault is unlikely. We will tackle the question whether parts of this fault farther to the north, beyond the *M*6.8 rupture area, and next to the south of the *M*7.8 rupture area, may show future activation.

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Syrian ground surface manifestations of the February 6, 2023- Kahramanmaras, Turkey M7.8 Earthquake

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The February 6, 2023 Kahramanmaras- Gaziantep Turkey M7.8 Earthquake, was one of the largest earthquake to hit Turkey in several decades. The event caused large number of death in Turkey and Syria. The earthquake resulted in thousands of totally collapsed building and thousands of damaged to the degree that are beyond repairs. The economic loses is not yet estimated but it can be said it is enormous in both countries. The quake devastated several provinces in south central Turkey and northwestern Syria. A fault rupture of 290 km long has been reported. The fault rupture correspond to several segments of East Anatolian Fault Zone. Intensity of ground shaking in the Mezoseismal zone is reported to exceed XI on MMI scale. Ground deformation is vast in Syrian side especially along the Al-Asi River flood plain. Liquefaction features is mapped and observed in serval bends in the flood plain. These liquefaction features are also observed inside village house in the developed part of the flood plain area. Sagging and subsidence of riverbank is observed and river rapids is reported. Subsidence along the Euphrates river flood plan is reported as far as 500 km at the Syrian Iraqi border.

Key words: Liquefaction, Al-Asi river flood plain

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Pre- and co-seismic surface displacements of 2022 Mw 6.7 Luding, China earthquake obtained by time-series InSAR

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On September 5, 2020, an Mw 6.7 earthquake occurred in Luding of Sichuan, China, which is located in the southern part of the Xianshuihe Fault Zone. This earthquake provides a new opportunity for studying the fault movement characteristics of this area. Reliable seismic cycle displacement results obtained by geodetic observation are the basis for the above study. Due to the dense vegetation coverage of the Luding area, the decorrelation is serious and it is difficult to obtain high-quality coseismic displacements by traditional 2-pass differential InSAR. To address this issue, we processed multi-interferometric pairs of Sentinel-1A of ascending and descending orbital directions by time-series InSAR method and extracted pre- and co-seismic information using a polynomial. The results show that: 1) The left region of Xianshuihe Fault moved toward SSE relative to the right region during the pre-seismic or interseismic period, moreover, the Gongga Mountain moved at a high rate. 2) The Luding earthquake caused significant surface displacements. Obviously, high-quality observations are more than the ones by traditional differential InSAR. Therefore, the technological process can be used to obtain seismic cycle displacements of other earthquakes with similar environments and conditions of observation.

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S12e - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

The 6 February 2023 Türkiye Earthquakes: Insights for the European Seismic Hazard and Risk Models

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The earthquakes that struck eastern Türkiye and Syria on 6 February 2023 force us to evaluate the models of seismic hazard and risk developed at the European scale for the region, specifically the 2020 European Seismic Hazard Model (ESHM20, Danciu et al.. 2021) and European Seismic Risk Model (ESRM20, Crowley et al.. 2021).

We first verified that the ruptures associated to the two main earthquakes are present within the inventory of ruptures within the source model (the earthquake rupture forecasts or ERFs) for the East Anatolian Fault (first event) and Sürgü-Cardak Fault (second event. Ruptures close in magnitude and dimension to those observed were present in the ESHM20 ERFs.

Preliminary ground motion observations were found to be consistent in their prediction of the expected shaking and its attenuation. Recorded near-fault ground motions also suggest strong pulse-like behaviour, indicating the need for such phenomena to be better captured in the GMMs.

We have finally run scenario risk calculations using the ESRSM20 site, exposure and vulnerability models for the two main earthquakes. Expected fatalities were lower than those reported at the time of writing; however, many factors contribute to this. Further analysis is on-going to understand the difference, but critical areas for future improvement to the risk models should include state-dependent fragility, modelling of further epistemic uncertainty in exposure and vulnerability, and inclusion of spatial- and temporal correlations in ground motions across a region.

List of ESHM20 and ESRM20 core team members (all co-authors of this abstract) on www.efehr.com

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The February 6th 2023 earthquake doublet in SE Türkiye: Spatio-temporal preparatory process and fault structure from an enhanced seismicity catalog

DOI: 10.57757/IUGG23-4524 - LINK

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On February 6th, 2023 at 01:17 UTC, a devastating M_W 7.8 earthquake nucleated on the Pazarcik segment of the East Anatolian Fault Zone (EAFZ) bounding the Arabian and Anatolian tectonic plates. The fault rupture included nucleation on a secondary fault branch of the EAFZ towards the SE of the main fault and a subsequent rupture propagation towards the NE and SW on the main EAFZ. This event was followed 9 hours later by an M_w 7.5 event on the Sürgü Fault about 100km to the North.

We evaluate the regional earthquake catalog provided by the Turkish Disaster and Emergency Management Presidency in the years leading up to the first mainshock and identify an acceleration in seismicity rates and seismic moment release in the very vicinity of the mainshock epicenter a few months before the earthquake in comparison to surrounding areas. First results show that this activity is concentrated in earthquake clusters on the secondary as well as main fault branch exhibiting low b-values around 0.6-0.7.

We develop an enhanced event catalog in the surrounding of the earthquake doublet spanning the time interval 01/01/2023-11/02/2023 using the Phasenet package and perform automatic P- and S-wave phase picking. Picks are associated into events using GaMMA software and single event and relative event locations are performed using NLLoc and hypoDD. The resulting enhanced event catalog presents the detailed view of the spatio-temporal evolution of seismic actvity around the mainshock epicenter framing the last stage of the preparatory process and the first few days of aftershock activity.

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S12e - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Predictability of great earthquakes: the 06 February 2023 M7.8 and M7.5 couple in Turkey

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The recent M7.8 - 27 km E of Nurdağı and M7.5 - 4 km SSE of Ekinözü, Turkey earthquakes provide another case history of the intermediate-term real-time prediction by the M8 algorithm (Healy et al. 1992, https://pubs.er.usgs.gov/publication/ofr92401; Kossobokov & Soloviev 2021, https://doi.org/10.1007/s12594-021-1907-8). The algorithm aimed at magnitude range M8.0+ determined Times of Increased Probability (TIP's) starting from July 2021 in the only three out of 262 circles of investigation that spread over most of the global seismic belts; the alert in one of them was confirmed in the next semi-annual updates, most recently in January 2023, eventually being marked by devastating earthquakes that hit Turkey on February 6, 2023. Note that (i) the epicentres of the two coupled events and their aftershocks are just outside the territory, where M8 algorithm aimed at M7.5+ magnitude range is applicable, while (ii) well inside the area of TIPs alerted for M8.0+ events, and (iii) some determinations of the first shock magnitude are equal 8.0 (e.g. GEOSCOPE Mw8.0, GS RAS Ms8.0, RETMC Mwp8.0).

The M8 prediction results accumulated over more than three decades of rigid real-time experiment provide reliable empirical constrains for modelling earthquake sequences and evidence that distributed seismic activity is a problem in statistical physics. Their accuracy is already enough for undertaking earthquake preparedness measures, which would prevent considerable part of damage and human loss, although far from the total.

The study is carried on in the framework of the Russian State Task of Scientific Research Works of IEPT RAS (0143-2019-0006).

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S12e - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

The 06 February 2023 Turkiye earthquake and tsunami in Eastern Mediterranean, performance of coastal structures in the Gulf of Iskenderun

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The earthquake (Mw=7.7) on 06 February 2023 (01:17 UTC) in Kahramanmaras, Turkiye caused a tsunami in the Eastern Mediterranean despite its strike-slip characteristic and epicenter (37.1123N 37.1195E) ~90 km inland. The earthquake ruptured at a shallow depth (~5) striking about NE-SW on the East Anatolian fault zone and having a devastating impact in southeastern Türkiye. Kandilli Observatory and Earthquake Research Center (KOERI), which is one of the Tsunami Service Providers of the UNESCO IOC NEAMTWS issued four tsunami messages with a tsunami warning 15 min after the earthquake with expected tsunami amplitudes more than 0.5 m. The generated tsunami was recorded at four tide gauge stations, (Iskenderun-Arsuz, Erdemli, Gazimagusa (Famagusta), and Girne (Kerinya) in the Eastern Mediterranean. The recorded water level fluctuations were analyzed after detiding to extract the arrival time of the wave and its profile. For the assessment of the 06 February 2023 tsunami, numerical simulations were performed using the tsunami numerical model NAMI DANCE to understand the generation mechanism and possible location. It is important to identify those features for future preparedness in the area. This small-scale tsunami has been an important reminder in this regard and a test for the effective working of the early warning system. A field survey was also performed on 11-13 February 2023 to investigate the tsunami traces, conduct eyewitness interviews and coastal structure performance evaluation. The simulations are repeated using the survey findings and the modeling results are compared with the measurements. The results will be presented with discussions.

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S13a - Development, Testing and Application of Earthquake Forecasting Models

SimplETAS: a reference earthquake forecasting model

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The Epidemic-Type Aftershock Sequence (ETAS) model is the most effective mathematical model to describe the short-term space-time clustering. The setup of the ETAS model is complicated by the high number of unknown and correlated parameters. The most recent ETAS parameterizations introduce the space-time variability of some parameters that make the model calibration even more arduous. Here, we investigate the ETAS model in an opposite perspective; we look for the simplest ETAS parametrization that can satisfactorily describe the short-term space-time earthquake clustering in crustal tectonic regions; we name this model simplETAS. Owing to its simplicity, simplETAS is easy applicable in almost all crustal tectonic regions. This ease of use leads implicitly to some important features that are worth being remarked; simplETAS provides i) important physical indications on which clustering parameter is mostly region and time-independent; ii) a reference model that can be used as benchmark to measure the relative forecasting skill of other models in earthquake forecasting experiments; iii) a simple but effective approach to generate synthetic earthquake catalogs of different length that can be used in seismic hazard and risk analysis, overcoming all problems related to the declustering and the Poisson assumption. Finally, we show that the simplETAS model calibrated with the Italian seismicity of the last decades is able to describe satisfactorily the space-time occurrence of the out-of-sample largest earthquakes in historical catalog.

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3D-ETAS model with depth-dependent trigger potential

DOI: 10.57757/IUGG23-0576 - LINK

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In the past decades, the Epidemic Type Aftershock Sequence (ETAS) model has been widely used for describing the occurrence and clustering of earthquakes in space and time. Because of large depth uncertainties in the past, this model is two-dimensional and uses only epicentral information. Current earthquake catalogs provide high-precision depth values that contain valuable information. Thus, we extend the spatiotemporal ETAS model to 3D versions exploiting the full hypocentral information of earthquake catalogs by incorporating a depth-dependent kernel into the trigger function. To explore its most appropriate parametric form, we first examine different triggering functions for the depth difference of the aftershock-mainshock pairs identified by the Nearest-Neighbor (NN) method, showing that a magnitude-dependent power-law kernel fits best the earthquakes data in Southern California. Therefore, in order to incorporate the earthquakes' depth information in the ETAS model, we extend the established 2D spatial power-law kernel by using hypocentral instead of epicentral distances. Furthermore, in our extended 3D-ETAS model, we consider space-dependent background activity, where we additionally allow for depth-dependent aftershock productivity. A first application to data from Southern California shows a good performance of the 3D model. We also find that the aftershock productivity strongly depends on depth, similar to the seismic moment released by the mainshocks, which may be related to depth-dependent seismic coupling.

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S13a - Development, Testing and Application of Earthquake Forecasting Models

Long-term recurrence pattern and stress transfer along the Kefalonia Transform Fault Zone (KTFZ), Greece: Implications in seismic hazard evaluation

DOI: 10.57757/IUGG23-0266 - LINK

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Large earthquakes ($M^{3}6.0$) recurrence pattern on specific faults is one of the key parameters for constructing Earthquake Rupture Forecast (ERF) models. These models are based on characteristic earthquake hypothesis and return the likelihood of the occurrence of a large earthquake in a specific time span either as a time-independent or an elastic-rebound motivated renewal process. Large earthquake occurrence is characterized by short- and long-term clustering segments due to the permanent and temporal stress changes and transfer as a potential factor to influence their recurrence by moving a fault towards or away from failure. We aim to investigate the long-term recurrence behavior of large ($M_w^{3}6.2$) earthquakes associated with the major fault segments of the KTFZ, which exhibits the highest moment rate release in Greece, with frequent occurrence of strong earthquakes with magnitudes $M_w^{3}6.0$ during both the instrumental and the historical era of seismicity. This data sample enables the detailed study of these earthquakes recurrence times, considering the effect of stress field evolution and stress transfer among the segments of the local fault network. Then, the Poisson and the Brownian Passage Time (BPT) distributions are applied, aiming at the development of both time-independent and renewal statistical models for earthquake generation associated with the KTFZ fault segments.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission – Euratom. Neither the European Union nor the granting authority can be held responsible for them.

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Enhancement of medium-term earthquake forecasting in New Zealand by incorporating strain-rate into the EEPAS model

DOI: 10.57757/IUGG23-0747 - LINK

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The “Every Earthquake a Precursor According to Scale” (EEPAS) model provides the medium-term component of public earthquake forecasts in New Zealand (NZ). EEPAS employs the “precursory scale increase” (Ψ-) phenomenon to forecast future earthquake occurrence rates with time-horizons up to a few decades. Ψ is the rate and magnitude increase of minor earthquakes preceding major earthquakes. Three associated predictive-scaling relations link mainshock magnitude , precursor time and precursory area .

Studies of Ψ in synthetic catalogues showed that the expected is inversely proportional to an overall reduction of fault slip rates. The slip-strain rate connection therefore motivates us to enhance EEPAS forecasts by incorporating strain-rate.

We allow the time distribution in EEPAS to depend on the strain-rate and introduce an additional parameter to quantify this dependence. Optimising the new parameter for the New Zealand catalogue confirms an inverse proportionality between the local strain-rate and the local precursor time. The information gain over the original EEPAS model is small because few target earthquakes occur where the strain-rate is low.
The forecast should be compensated for incompleteness of precursory earthquake contributions due to the limited lead-time from the start of the catalogue to the occurrence of target earthquakes. The incompleteness is especially severe for low strain-rate areas where is longer. Further incompleteness can result from the precursory area for some target earthquakes extending outside the region covered by the catalogue. Such considerations should improve forecasting for low strain-rate areas.

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New insights from the Collaboratory for the Study of Earthquake Predictability (CSEP)

DOI: 10.57757/IUGG23-4872 - LINK

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The global Collaboratory for the Study of Earthquake Predictability (CSEP, https://cseptesting.org) advances rigorous research into earthquake forecasting through open science practices. These include, foremost, a dedication to testing forecasts in a truly prospective manner, along with strict standards for reproducibility, community-endorsed model evaluation approaches, and open-source software. Now operating for over 15 years, CSEP recently re-invented itself with a modern community-developed open-source Python software toolkit (pyCSEP), a broader range of model classes and evaluations, and better open access to models, data and test results through reproducibility packages. This reinvention facilitated a surge in new research, driven largely by a global and engaged early career researcher community. In this overview talk, I will review the progress and new insights this has generated.

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S13b - Development, Testing and Application of Earthquake Forecasting Models

Application of an adaptive Bayesian spatio-temporal aftershock forecasting workflow on the 2023 southern Turkey seismic Sequence

DOI: 10.57757/IUGG23-3650 - LINK

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Department of Structures for Engineering and Architecture, Napoli, Italy
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[3]University of Potsdam, Institute of Geosciences, Potsdam, Germany
[4]GFZ, German Research Center for Geosciences, Potsdam, Germany

A powerful seismic sequence struck the Turkey-Syria border on Feb. 6 with three earthquakes having M>6.5. At 01:17 UTC, a M7.8 earthquake occurred that was followed 11 minutes later by a M6.7, and around nine hours later by a M7.5. In the first 24 hours, 20 aftershocks with M>5 and 68 events with M>4 have been registered.

Recently, we have improved and tested a Bayesian simulation-based workflow for spatio-temporal early seismicity forecasting based on ETAS model. It exploited the versatility of the Bayesian inference to adaptively update the forecasts based on the incoming information from the ongoing sequence. This workflow is demonstrated and verified through retrospective early seismicity forecasting of Central Italy 2016 and the 2017-2019 western Iran seismic sequences.

We test this workflow to predict the spatial distribution of events and their uncertainties for various forecasting intervals within this seismic sequence. Bayesian updating is first employed to learn the ETAS model parameters conditioned on the registered events (that already took place). Then, plausible sequences of events during the forecasting interval are adaptively generated. To this end, we strive to simulate those plausible sequences by embedding a branching process formulation inside the proposed workflow as an alternative to the piece-wise stationary integration of the conditional rate. The latter could be a new feature to the forecasting workflow, while its efficiency in providing early forecasts is explored during this study.

This work has been supported by PRIN-2017 MATISSE project No 20177EPPN2, funded by Italian Ministry of Education and Research.

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Future scenarios for induced seismicity at the Groningen gas field, Netherlands

DOI: 10.57757/IUGG23-1188 - LINK

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Section 2.1: Physics of Earthquakes and Volcanoes, Potsdam, Germany

The Groningen gas field is one of the most frequently considered sites for studying induced seismicity. The public concern about seismic activity increased drastically with the M3.6 Huizinge earthquake in 2012. Since then gas production has been reduced and is planned to be terminated soon. In our study we first present statistical estimates of the maximum possible magnitude based on the earthquake catalog from 1991 until present. Second, future scenarios for seismicity are calculated for various statistical and physical models using gas production scenarios and simulated stress values until 2052. We find that a model based on rate-and-state dependent friction with additional aftershocks fits best to the data. Despite the overall decreasing earthquake rate resulting from decreasing production volumes, the findings indicate a considerable probability that the maximum expected magnitude in the next 30 years exceeds the maximum observed magnitude from the past 30 years.

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Estimating numbers of fatalities in likely future earthquakes

DOI: 10.57757/IUGG23-0012 - LINK

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Estimating the size of future earthquake disasters by fatality numbers (Fat) is possible with a useful accuracy. Governments, first responders and the population in a seismically active region can be told whether they must be prepared for major, medium, or small numbers of earthquake fatalities. Most of the fatality calculations with the tool QLARM made within minutes after earthquakes worldwide have been correct within factors of 2 to 3, or better. We expect that estimates of future numbers of fatalities are also in this range of accuracy. We follow these steps. 1) We verify that QLARM fatality estimates are correct to better than a factor of 2 for historic earthquakes. 2) We identify an active fault segment, L(local), that has not ruptured recently, and that may break in one event. 3) We estimate the magnitude, M(local), from the known relationship between L and M. 4) We calculate the number of fatalities for a line rupture of L(local), with M(local) and the local attenuation determined in step (1). 5) The data on building stock quality is contained in the program. We have estimated future earthquake fatalities in the Himalaya, China, Kirghizstan, Greece, Italy, Haiti, Portugal, Algeria, Spain, and Morocco. We have found that some regions contain only short faults typically $L \leq 30$ km, implying $M \leq 6.5$ and resulting in Fat < several hundreds. In regions with $L \approx 100$ km and 300 km, respectively (M7+ and M8) ruptures result in several thousand and several tens of thousand fatalities, respectively.

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Seismic hazard parameters inferred from earthquake catalogues with time-varying completeness

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The maximum likelihood estimation of the earthquake frequency-magnitude parameters (the Gutenberg–Richter *b*-value, the mean seismic activity rate and the area characteristic maximum possible earthquake magnitude is provided in the case of a time-varying level of completeness. In several recent studies, the catalogue with the time-varying level of completeness is defined as one that can be divided into sub-catalogues, each with a sharp jump of. This work provides a maximum likelihood estimator of the earthquake frequency-magnitude parameters when the time-varying level of completeness is a continuous, smooth function without "jumps" and abrupt changes.

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S13c - Development, Testing and Application of Earthquake Forecasting Models

Forecasting earthquakes in the United States from short to long timescales

DOI: 10.57757/IUGG23-2045 - LINK

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[3]United State Geological Survey, Earthquake Science Center, Pasadena, USA

Statistical earthquake forecast models are a critical component of several products released by the U.S. Geological Survey as part of its mission to deliver actionable information to decision makers in the US. These include the National Seismic Hazard Model (NSHM) and Operational Aftershock Forecasts (OAF), the latter of which can include swarm forecasts. Both products require earthquake forecast models that are applicable on different timescales, ranging from days to years (OAF) to decades (NSHM). OAF uses short-term forecast models that are based primarily on catalog statistics and include clustering behavior, such as encompassed in Reasenberg and Jones (1989), the ETAS model (Ogata, 1988), and swarm models (Llenos and van der Elst, 2019). The NSHM uses a long-term (50-year) earthquake forecast, one component of which is a smoothed seismicity model based on an earthquake catalog. Clusters are removed when forecasting the location of future seismicity but retained when estimating the future earthquake rate. Both OAF and the NSHM face challenges in catalog incompleteness, in both the short term and the long term. And both may be affected by anomalous earthquake rate changes, such as natural earthquake swarms, human-induced seismicity, or volcanic events. In this presentation, I will give an overview of the statistical models that are used for these two products, updates that have been made to address some of these challenges, future updates that could be considered such as the use of machine learning methods, and how the forecasts are used and presented to the public.

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S13c - Development, Testing and Application of Earthquake Forecasting Models

Developing guidance to communicate global aftershock forecasts

DOI: 10.57757/IUGG23-4869 - LINK

Max Schneider[1], Sara K. McBride[1], Nicholas van der Elst[2], Jeanne Hardebeck[1], Andrew Michael[1], Morgan Page[2]
[1]United States Geological Survey, Earthquake Science Center, Moffett Field- CA, USA
[2]United States Geological Survey, Earthquake Science Center, Pasadena- CA, USA

The U.S. Geological Survey (USGS) is responsible for public aftershock forecasts following US earthquakes. An automated system produces forecasts for most M5+ earthquakes. While this system is not operational for earthquakes outside the US, the USGS has received requests for forecasts following damaging earthquakes worldwide, particularly those with a high number of fatalities (orange or red level on the PAGER scale). However, aftershock forecasting globally has the inherent challenge of communication across different languages and cultures. Further, aftershock forecasts made from outside the affected region can be a challenge for local science communicators because they may need to respond to questions about a forecast that they may not be familiar with themselves. Effective communication of aftershock forecasts for earthquakes across the world requires developing products that can serve non-English-speakers, and providing local science communicators with tools to help them respond to questions about the forecasts. To support the communication of aftershock forecasts globally, the USGS is developing additional public tools for local science communicators. A communication guide will accompany the forecast template and will be translated into multiple languages. To develop this communication guide, we are facilitating meetings with science communicators in different countries to solicit feedback on its components. Additionally information regarding protective action will be updated. The USGS currently recommends "Drop, Cover, and Hold On", which may not be appropriate in countries with poorly constructed buildings. By developing additional communication tools, aftershock forecasting will be more effective and accessible to reduce seismic risk worldwide.

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S13c - Development, Testing and Application of Earthquake Forecasting Models

Earthquake forecasting in New Zealand: Past, present and future

DOI: 10.57757/IUGG23-5040 - LINK

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Researchers from New Zealand have engaged in developing and testing earthquake forecasting models for many decades. The existing earthquake forecasting models can be classified into three categories, (1) short-term or aftershock models that describe the decay of the earthquake occurrence rate following a large event, (2) medium-term models that are variations of the Every Earthquake a Precursor According to Scale (EEPAS) model, which is based on the observation that the size and frequency of earthquake occurrence tends to increase in the vicinity of an upcoming large earthquake and aims to forecast upcoming large events in the coming months to decades, and (3) long-term models.

In 2010, following the M7.1 Darfield earthquake that initiated the Canterbury earthquake sequence, GNS Science began to provide earthquake forecasts to the public. There were several further earthquake responses over the years, the largest being the 2011 M6.2 Christchurch earthquake and the 2016 M7.8 Kaikoura earthquake.

A new automated seismic processing software, introduced in 2012, caused inconsistencies in the earthquake catalogue, especially with magnitudes. It has been a slow process to resolve these issues. In the meantime, we have been limited to forecast earthquakes of magnitude 5 and larger.

In the future, we envisage to have an automated system provide regular earthquake forecasts to the public, and to engage more with users to provide the information that they need for decision-making in a seismic crisis and for planning for earthquake resilience.

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S13c - Development, Testing and Application of Earthquake Forecasting Models

Good practices in developing, testing and communicating earthquake forecasts: an expert elicitation

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Strong earthquakes are followed by numerous aftershocks, which themselves can be strong and devastating, sometimes even stronger than the initial main event. Although earthquakes cannot be predicted, the occurrence of aftershocks in space, time, magnitude and numerosity follows several universally observed empirical laws. Operational earthquake forecasting (OEF) systems aim to provide a probabilistic assessment of expected earthquake occurrence in near-real time, enabling informed decision-making for civil protection, authorities, the public, or other user groups.

While few agencies worldwide have OEF systems in place, most countries, even those in regions of high seismic hazard, only estimate the time-independent, long-term earthquake probability as part of their seismic hazard and risk assessment, which serves a different user group involved in long-term decision making. This lack of OEF systems may be due to a lack of data, knowledge, resources, or guidance required to build them. With a plethora of forecasting models and testing schemes published every year, it is difficult to choose the most appropriate ones. On top of technical choices involved in the development and testing of forecasting models comes the additional challenge of communicating forecasts to users.

In our study, we conducted an elicitation of expert views on these topics, aiming to provide good practice recommendations for the development, testing and communication of earthquake forecasts. We applied the Delphi method – with two surveys and one workshop – to identify consensus and dissent among a group of 20 international earthquake forecasting experts on these issues, and here present the results of this elicitation.

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S13d - Development, Testing and Application of Earthquake Forecasting Models

Mega-thrust earthquake potential along the subduction zone of Peru based on the earthquake energy-budget

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We investigate earthquake potential of megathrust earthquakes in Peru based on the interseismic coupling model at the subduction interface (ISC) (Villegas-Lanza et al. 2016). Northern Peru displays a shallow and weak ISC, whereas Central and Southern Peru are highly coupled. Recent studies in the Nankai-Tonankai subduction region in Japan indicate that slip deficit regions do not directly reflect the local frictional strength characteristics controlling fault slip behavior at the plate interface (Noda et al. 2021). Therefore, to investigate the necessary conditions for megathrust earthquake generation we calculate the difference between accumulated strain energy during the interseismic period, with fault fracture energy (G), for a given slip scenario. A scenario cannot occur unless the accumulated strain energy exceeds G. To calculate G we use a scaling between average fault slip and G for subduction interface earthquakes, obtained from the NEIC global dataset of finite fault slip rupture models (Hayes et. al, 2017), and the 2D finite width slip dynamic rupture model (Pulido 2022).

We calculated the shear stress accumulation rate and total accumulated shear stress at the Peruvian subduction margin, based on the slip deficit rate model, and interseismic periods since the largest historical earthquakes for the Northern, Central and Southern segments of the subduction interface. Our results indicate that the Central segment in Peru has currently accumulated the largest amount of shear stress, corresponding to an earthquake up to Mw~8.8. Using the earthquake energy balance we quantified the necessary conditions for megathrust earthquake generation across the subduction margin in Peru.

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S13d - Development, Testing and Application of Earthquake Forecasting Models

Assessing seismicity and magnitude distributions for NE Brazil earthquake catalog for Seismic Hazard Analysis purpose

DOI: 10.57757/IUGG23-0141 - LINK

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[2]Institute of Geophysics Polish Academy of Sciences, Department of Seismology, Krakow, Poland

Results of the probabilistic analysis of stationary seismic hazard considerably depend on the quality of the data declustering and the reliability of distribution models for the earthquake occurrence and magnitude. We studied the NE Brazil catalog to optimally perform the aftershock removal and select the best distribution models. For such analysis, events from 1990 onward were collected from the Brazilian Earthquake Catalogue (SISBRA). First, we determined the magnitude completeness (mc) using maximum curvature, 90%, and modified goodness of fit approaches. Subsequently, we applied two declustering methods of Gardner and Knopoff (1974) and Reasenberg (1985) and compared the results. Reasenberg's (1985) declustering algorithm was chosen as being less conservative. The Anderson-Darling test was applied to test the exponentiality of both the interevent time and magnitude distribution. We tested the complete dataset and separately the data from the time periods in which monitoring setups had been different. In every case, the test rejected the exponentiality of the interevent time distribution. The magnitude distribution of earthquakes from the complete dataset also disagreed with the exponential distribution. However, separate tests of the data from selected spatially subsets unveiled nonrejection of exponentiality for 3 out of 4 most seismically active areas.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, and CNPq (Brazil) grants. It was also partially supported in the framework of the statutory activity from the subvention of the Ministry of Science and Higher Education of Poland.

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S13d - Development, Testing and Application of Earthquake Forecasting Models

Seismicity Analysis and Probabilistic Hazard Assessment of earthquakes in a circular region of 2005 Kashmir Earthquake of the North-West Himalaya

DOI: 10.57757/IUGG23-0087 - LINK

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ABSTRACT
Spatial distribution of seismicity and seismic characteristics like b-value, fractal dimension, energy release and recurrence period are assessed for the circular region of radius 400 km, taking epicenter of 2005 Kashmir earthquake (34.45°N -73.65°E) as Centre. The EHB relocated earthquakes $M_b \geq 3.8$ are selected for the period 1964-2020 from the International Seismological Centre catalogues.

The Maximum Likelihood Method (MLM) and Least Square Method are used for calculating b-value. The fractal dimension is estimated using the correlation integral method. The events are also used for estimating radiated energy in the region. The probability of occurrence of moderate earthquakes ($M_b \geq 6.0$) during a specified interval of time has been estimated on the basis of four probabilistic models namely, Exponential, Weibull, Gamma and Lognormal. The cumulative and conditional probabilities are estimated using the above four probabilistic models. The model parameters have been estimated by the Maximum Likelihood Estimates (MLE). It is estimated that there is a 99% probability for occurrence of at least one earthquake of magnitude $M_b \geq 6.0$ in this region in a time window of four-five years from the year 2019.

Probability density function maps, using Poisson distribution for the magnitude $M_b \geq 6.0$, were prepared. These maps are used to estimate the percent probability of occurrence of next event with different return periods. The vulnerable zones identified by different spatial distribution maps are further corroborated with the probabilistic models to assess the seismic hazards in the region.

Keywords: Seismic Hazards, Seismological parameters, Probability Distributions, return periods

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Three Dimensional reference model of the Indian tectonic plate and intraplate stress field distribution

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Scientists frequently used stress changes to evaluate seismic hazards. A 3D mechanical model of the Indian plate has been considered to simulate the stress and strain distribution using finite element method (FEM). The model is divided into 19 geological regions, and each 19 parts is sub-divided into five layers, and for each layers different elastic parametric values are given and the effect of the material heterogeneity is studied. It is observed that in comparison to homogeneous model, heterogeneous model shows close correlation with GPS measurement. Also, the stress distribution contour estimated by the homogeneous model is compared with the seismotectonic map of the Indian subcontinent but it does not agree as homogeneous model estimates a low-stress value (~180 MPa) in highly seismically active regions like Indo-Burmese region, the Himalayan region and the Andaman arc region. While, heterogeneous model shows high stress of the order of 60 MPa–10^5 MPa at the Himalayan plate boundary, Indo-Burmese region, Andaman arc, Indian Mid-Oceanic, and some parts of the Saurashtra and Southern Granulite regions and is able to reasonable capture the regional stress distribution of the Indian plate. It is concluded that the average stress difference caused by neglecting the heterogeneity is ~ 10–20 MPa, which is 100 times larger than the triggering stress (0.1 MPa). Which will be useful to assess the seismic hazard to identifying seismically active zones by interpreting the strain rate and stress distribution affecting the location and size of earthquake due to lithospheric and regional lateral heterogeneity.

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S13d - Development, Testing and Application of Earthquake Forecasting Models

Spatiotemporal analysis of background seismicity identified by different declustering methods

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A large number of studies aimed at seismic hazard assessment and earthquake forecasting relies on the assumption that background seismicity is a realization of a homogeneous Poisson process over time, though not necessarily in space. In this study a statistical analysis is performed to assess whether the background seismicity, as identified by different declustering methods, holds the spatio-temporal features typical of such a Poisson process. Various spatiotemporal measures are applied to quantify the residual space and time clustering in the background seismicity, which can be used to assess the performances of the declustering methods in removing the spatiotemporal clustering patterns from the full catalogue. Specifically, the Allan Factor (AF) and the Markov Modulated Poisson Process (MMPP) are used for the analysis of time patterns, while the Morisita Index (MI) is used for space clustering analysis.

To exemplify the proposed procedure, two declustering methods, namely the Nearest Neighbour algorithm (Zaliapin and Ben-Zion, GJI 2016) and the Stochastic Declustering algorithm (Zhuang et al., JGR 2004), are applied to identify the background seismicity of Northeastern Italy. Our results show that the time correlation and the space clustering are reduced, but not totally eliminated, in declustered catalogues. Moreover, we found that the MMPP with multiple states is a more suitable background seismicity model than the traditional homogenous Poisson process. These results are well consistent with those obtained for Northern Algeria (Benali et al., Axioms, 2023), showing that none of the adopted declustering methods totally eliminated the spatiotemporal clustering from the full earthquake catalogue.

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S13e - Development, Testing and Application of Earthquake Forecasting Models

Quantifying the probability and uncertainty of multiple-structure rupture and its recurrence intervals for Taiwan

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This study identifies structure pairs with the potential for simultaneous rupture in a coseismic period and quantifies their rupture recurrence intervals. To assess the potential for a multiple-structure rupture, we calculated the probability of Coulomb stress triggering between seismogenic structures. We assumed that a multiple-structure rupture would occur if two structures could trigger each other by enhancing the plane with thresholds of a Coulomb stress increase and the distance between the structures. We discussed the uncertainties of multiple-structure rupture pair identification from various thresholds of stress change and structure distances, effective friction coefficient, and rotation of rake angles. Note that since our approach is based on static Coulomb stress change, the possibility of a multiple-structure rupture in a coseismic period might be overestimated. To estimate the recurrence intervals for multiple-structure ruptures, we implemented a scaling law and the Gutenberg-Richter law. Considering that a single structure may be involved in multiple cases of multiple-structure ruptures, we developed new formulas for slip partitioning in a complex fault system. We discussed the uncertainty of recurrence interval from epistemic uncertainties from deviations of slip rate and rupture area, various empirical formula of rupture parameters. Due to a larger characteristic magnitude and a larger displacement of the multiple-structure rupture, the rupture's recurrence interval could be longer. Therefore, considering the multiple-structure rupture leads to an increase in seismic hazard in a long return period, crucial for the safety evaluation of infrastructures.

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ECS Awardee 2023: Abnormal low-magnitude seismicity preceding the M6.4-M7.1 2019 Ridgecrest (California) sequence and the M7.1 2018 Anchorage (Alaska) earthquake

DOI: 10.57757/IUGG23-2889 - LINK

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Experimental studies suggest that large, locked faults accumulate stresses both on themselves and in their surroundings, producing changes in low-magnitude seismicity patterns on regional scales. Still, the complex spatiotemporal distribution of low-magnitude seismicity, in conjunction with the incompleteness of previous earthquake catalogs, hinders determining whether large seismic events are unequivocally preceded by some kind of seismic or tectonic unrest. This can be alleviated in the near future thanks to the advent of new machine learning-based methodologies, which offer alternative ways to recognize subtle and non-linear hidden patterns from previous experience. Here, we explore with a new multivariate, supervised, machine learning-based algorithm whether low-magnitude seismicity hides robust, non-linear, precursory patterns that may unequivocally alert of impending large magnitude earthquakes. Our algorithm, which integrates a random forest machine learning approach and statistical features built from openly-available earthquake catalog data, reveals that the M6.4-M7.1 2019 Ridgecrest (California) sequence and the M7.1 2018 Anchorage (Alaska) earthquake were preceded by up to ~3 months of tectonic unrest on regional scales, as evidenced by abnormal low-magnitude seismicity that spread over ~15-25% of the total area of Southern California and Southcentral Alaska. Our analysis is further supported by finite element solid mechanics models which show that the existence of large, locked faults can increase the average shear stress in surrounding areas by up to ~80% upon constant compressional loading. These findings may open up new perspectives for surveillance agencies to detect when a region approaches an earthquake of great magnitude weeks to months before it occurs.

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S13e - Development, Testing and Application of Earthquake Forecasting Models

Impacts of uncertainties in fault network geometry on a physics-based earthquake simulator

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Recent multifault ruptures, such as the 2010 El Mayor-Cucapah and 2016 Kaikōura earthquakes, have demonstrated the potentially complex interactions of faults in single earthquakes, contrasting with the typical assumption of characteristic fault ruptures in seismic hazard assessment. Physics-based earthquake simulators, such as RSQsim (Dieterich & Richards-Dinger, 2010; Richards-Dinger & Dieterich, 2012), offer one approach to understanding potential multifault earthquakes, and their effects on the time-dependence of earthquake recurrence. Here we investigate the effects of known uncertainties in fault-network geometry on the outputs of such simulators. We use the Canterbury and North Marlborough regions of the South Island of Aotearoa New Zealand – the epicentral region of the 2016 Kaikōura earthquake – as a case study. Using recently developed fault modelling tools, we create 3D fault networks corresponding to a range of possible fault-network geometries in the region, including the potential for missing faults and variable geometries at fault intersections. The different networks we develop are motivated by key observations from the Kaikōura earthquake, such as the high proportion of previously unmapped faults in the rupture (Litchfield et al., 2018), and by explicit uncertainties in the New Zealand Community Fault Model (Seebeck et al., 2022). We generate synthetic earthquake catalogues on these different fault networks and investigate their similarities and differences, both statistically and in terms of the generated multifault ruptures. By doing so, we are able to better understand how the "known unknowns" of fault-network geometry impact earthquake simulator outputs.

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S13e - Development, Testing and Application of Earthquake Forecasting Models

Tsunami threat estimation from physics-based earthquake simulators. Application to the Carboneras Fault, Western Mediterranean.

DOI: 10.57757/IUGG23-3858 - LINK

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The study of tsunami hazard is frequently approached from numerical modelling in a deterministic or probabilistic way. When probabilistic assessments are developed, epistemic and aleatory uncertainties are taken into account and incorporated into logic-tree and Monte Carlo approaches. Our approach is based on the use of physics-based earthquake simulators, developed in recent decades to overcome the temporal limitation of the instrumental seismic catalogue in probabilistic seismic hazard assessment (PSHA). Recent development of numerical codes based on the rate-and-state constitutive law for fault slip and frictional behaviour (RSQSim) allows also the modelling of the short-term rupture process based on a quasi-dynamic physical approximation. We have applied this model to the Eastern Betic Shear Zone, where one of the major faults of the western Mediterranean is present, the Carboneras Fault. This fault is a left-lateral transpressive structure oriented with a length of ∼150 km, most of them offshore, and a slip rate of 1.3 mm/yr. This fault has been proposed as source of the 1522 Almeria earthquake (Int. VIII-IX) possibly related to a local tsunami. We present tsunami simulations from seismic ruptures of a 1 Myr synthetic seismic catalogue generated with RSQSim, consistent on 773,893 events with magnitudes Mw 3.3 - 7.6. The Carboneras Fault has the capacity to generate locally damaging tsunamis. The frequency - magnitude distribution of the seismic catalogue departs from the classical Gutenberg-Richter potential relation showing a bell-shaped distribution for the bigger events. The inter-event times for the maximum earthquake magnitudes are between 2000 and 6000 years.

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S13e - Development, Testing and Application of Earthquake Forecasting Models

The observed variability of seismic dynamics in the Pacific Northwest

DOI: 10.57757/IUGG23-0382 - LINK

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To gain new insight into patterns of earthquake activity in the Pacific Northwest we study regional seismic dynamics in terms of several moving averages. In particular, the variability of the Unified Scaling Law for Earthquakes (USLE) coefficients in 3D have been evaluated at the three separate seismic focal zones – Southern Kamchatka, Northern Kamchatka, and Commander segment of Aleutian arc.

USLE states that the logarithm of expected annual number of earthquakes of magnitude M or larger in an area of linear dimension L follows within the magnitude range [M–,M+] the relationship $\log N(M,L)=A+B\times(5-M)+C\times\log L$, where A, B, C are empirical constants. Naturally, USLE compliments to a- and b-values of the Gutenberg-Richter relationship with C, an estimate of fractal dimension of epicentres at a given site. USLE allows for realistic rescaling seismic hazard to the size of exposure at risk and its scaling parameter η controls regional distribution of inter-event times.

We considered shallow and intermediate depth earthquakes with magnitude $M \geq 4.0$ in 1996–2020 reported in the open access database of the Kamchatka Branch of GS RAS.

The results show up distinct statistically significant differences in the southern and the northern segments of the Kamchatka slab as well as in the western segment of the Aleutian arc. The plots of the three USLE coefficients in 3D display their complex correlation patterns of different type in the preselected volumes of seismic genesis.

The study is carried on in the framework of the Russian State Task of Scientific Research Works of IEPT RAS (0143-2019-0006).

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Development of seismic process before the M 8.3 Illapel, Chile, 2015 Earthquake observed in an equivalent dimension space

DOI: 10.57757/IUGG23-0923 - LINK

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The dynamics of seismic processes is expressed by non-random, stochastic characteristics of seismic series. Investigating these characteristics may assist in solving earthquake prediction problems. We approach the seismic process development employing the probabilistic transformation to equivalent dimension (ED) space of earthquake parameters. The present research concerns the seismic process preceding the magnitude 8.3 Illapel, Chile, 2015. The seismic catalog is reparametrized. The new parameters of seismic events are interevent time, orthodromic epicentral distance, and magnitude. Then these parameters are transformed to ED space by adopting a non-parametric kernel estimation method. The transformed parameters are now comparable, and the distance between the earthquakes in ED space is Euclidean. We trace the changes in time of the average distance between earthquakes in the ED space, calculating this distance in sliding data windows of the same number of earthquakes. The results exhibit distinct and statistically significant changes in the two years preceding the Illapel mainshock. The average distance between earthquakes increased from 2013 to the midst of 2015. Then the distance decreased until the mainshock in September 2015. A similar pattern was obtained in the previous study of seismicity clustering before the magnitude 8.2 Tehuantepec, Mexico, 2017 earthquake, though in the Tehuantepec earthquake's case, the systematic changes of the average distance between earthquakes before the mainshock lasted longer, some eleven years.

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New clues for seismic hazard from statistical properties of seismicity, rheology and tectonics

DOI: 10.57757/IUGG23-0123 - LINK

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Probabilistic seismic hazard models are usually grounded on a basilar statistical analysis of recent and historical seismicity, and only a small number of them also considers the local geodetic strain and the discrete seismogenic sources. Nevertheless, a large amount of information is buried in spatial and temporal time series as well as in the geophysical properties of the different tectonic settings. Here, we show some preliminary results about the connection between advanced statistical properties of seismicity, rock physics, tectonics and the mid-/long-term seismogenic potential. The role of local and global, spatial, and temporal clustering of seismic events is deeply analysed also with reference to local geodynamics and other routinely investigated features of seismicity, e.g., the b-value of the Gutenberg-Richter law.

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S14a - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Complex ground deformation of the 2016 Mw 6.5 central Italy earthquake influenced by the geological structures and seismicity distribution

DOI: 10.57757/IUGG23-4384 - LINK

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Istituto per il Rilevamento Elettromagnetico dell'Ambiente IREA, Napoli, Italy

The 2016 Mw 6.5 earthquake struck a large region of the Apennines in central Italy and produced impressive and complex surface ruptures. These ruptures were investigated and mapped by field geologists for years after the earthquake thanks also the use of remote sensing data.
Here we present detailed maps of the ground deformation pattern produced by the Vettore normal fault activated during the Mw 6.5 mainshock, using Differential Synthetic Aperture Radar Interferometry. The DInSAR analysis has been retrieved from ALOS-2 SAR data, via the Parallel Small BAseline Subsets (P-SBAS) algorithm. At the local scale, we automatically identify many surface ruptures, most of which already observed in the field. At the large scale, we trace a set of five geological cross-sections to inspect a possible link between the coseismic vertical displacement, the lithology distribution and the tectonic structures of the area (i.e., thrusts, normal faults). On these sections, we also project the seismicity distribution recorded during October 2016.
The integration of such datasets allows the recognition of an important geological control in the overall distribution of the deformation, which shows maximum values in correspondence of the carbonatic multilayer and minimum values within the clastic succession. The distribution of seismicity allows also us to distinguish seismogenic by aseismic slip associated with fault ruptures.
The results of this work demonstrate that the integration of surface geology, remote sensing data and seismicity, can lead to a better understanding of the influence of geological structures on the distribution of the ground deformation associated with earthquakes.

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S14a - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Estimating the background stress fields in the source region of the 2016 Kumamoto earthquake based on shear strain energy

DOI: 10.57757/IUGG23-0404 - LINK

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[3]National Institute of Advanced Industrial Science and Technology, Research Institute of Earthquake and Volcano Geology, Tsukuba, Japan

We aimed to estimate the background stress field prior to the 2016 Kumamoto earthquake sequence, examining temporal changes in elastic strain energies from various aspects. Firstly, we modeled the six components of the background stress fields by examining the fault orientations relative to the stress orientation, and by assuming the Coulomb failure criterion with three apparent friction coefficients of m' = 0.4, 0.2, and 0.1. We also calculated coseismic stress change fields due to the largest preshock and the mainshock of the sequence, using the slip distributions of the events and slip response function. We obtained three (absolute) stress fields immediately after the mainshock, superposing the coseismic stress changes fields on the background stress fields. In the case of m' = 0.4, the larger slip contributed to release shear strain energies more. We found similar tendency in the case of m' = 0.2 except for the shallow part with large slip on the Hinagu fault. In the case of m' = 0.1, on the other hand, large slip in most shallow parts contributed to increase shear strain energies. The results with m' = 0.1 are inconsistent with that earthquakes are physical process to release shear strain energies. This perspective is supported by further analyses on the relation between temporal changes in slip and shear strain energies and temporal changes in stress orientation. We concluded that the background stress fields with m' = 0.4 can be the most rational, and that the source region is in the Anderson-Byerlee stress condition.

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S14a - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Tectonic Geomorphology in KwaZulu-Natal (KZN), South Africa: Active faulting background for the 31/12/1932, MW 6.9 earthquake

DOI: 10.57757/IUGG23-2737 - LINK

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The characterisation of faults within intraplate regions, especially those with longer seismic cycles, is beneficial to the improvement of seismic hazard assessment. In southern Africa, the link between the instrumental, historical, and paleo-seismic activity with active faults is often difficult due to low seismic strain rate (< 1 mm/yr) and sparse distribution of seismic stations. The relatively low level of seismic activity and low deformation rate require an understanding of the long-term active tectonics and recurrence interval of large and damaging earthquakes. Here, we perform detailed reanalysis of the 1932 St Lucia earthquake, as well as investigations in seismotectonics and tectonic geomorphology in the Kwazulu-Natal region, with the objective of characterising physical parameters of active faults necessary for seismic hazard assessment. First, we delineate the seismic and tectonic characteristics of the E-W and ENE-WSW trending Tugela and Greytown fault scarps, respectively, as a structural background of past earthquakes. We proceed with the description of geomorphic markers of fault scarps using tectonic geomorphology. Airborne magnetics added with electrical resistivity tomography and seismic reflection profiles are used as ground geophysical methods to further investigate physical fault geometries. The integration of these studies shows evidence of active faulting with right lateral offsets along the Tugela and Greytown fault scarps. The late Quaternary tectonic activity and characteristics of the Tugela fault suggest a possible correlation with the 1932 earthquake. Field investigations along fault scarps combined with geophysical and seismotectonic studies will likely lead to a realistic seismic hazard assessment in the KZN region.

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S14a - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Active shear system in Southern Egypt: New insights from sin el-kaddab area, SW aswan

DOI: 10.57757/IUGG23-0035 - LINK

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Numerous active shear systems can easily be detected in the Eastern and Western Deserts (ED & WD) of Egypt. The Nubia Shear System (NSS) is an eye-catching structural feature in the extreme southern part of the WD. The NSS is typified by two main trends; E-W and N-S. Propagation of shearing along both trends resulted in the formation of different styles of shear zone-related folding reflecting transtensional and transpressional regimes. The present work is an integrated field/structural and seismological approach aiming to decipher the recent activity and seismic hazard potentiality of the NSS. Several lines of evidence indicate recent activity including topographic expression and intensive degree of shearing, and severe fragmentation and pulverization. Such activity led to low to moderate earthquakes with magnitude up to 5.6 ML. The full moment tensor inversion, which was decomposed it into three parts Isotropic (ISO), Double Couple (DC) and Compensated Linear Vector Dipole (CLVD), offers further information about the NSS. The obtained complete focal mechanism for the whole district is characterized by non-DC components which have been represented by ISO and CLVD with average value 22.2 % and 34.4 % respectively, and DC components with average value of 39.1 %. The focal mechanism solutions (FMS) for earthquakes in the concerned area demonstrate two nodal E- to ENE- trending planes, with subordinate right-lateral strike-slip component, and N- to NNW- trending planes, with left-lateral strike-slip component. The directions of tectonic extension (T) and compression (P) are NNE-SSW and NNW-SSE, respectively.

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S15a - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

Resolving dynamic and chemical features of the lowermost mantle from global seismic tomography

DOI: 10.57757/IUGG23-2495 - LINK

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We apply a variety of statistical and machine learning techniques to elucidate the key 1-D and 3-D features of Earth's lowermost mantle as imaged by seismic tomography. Multiple observables are required to break the trade-off between temperature, composition and mineral phase changes. Using bulk and shear wave speeds we can distinguish lateral and vertical variations in silica content and place a broad constraint on the temperature. Including density allows us to further resolve variations in iron content and place a tighter constraint on the temperature. Globally, the base of the mantle appears to be enriched in SiO2 compared to the overlying mantle. We demonstrate that the large low shear velocity provinces (LLSVPs) are more likely to be enriched in post-perovskite than their surroundings, and that dense piles at the base of the LLSVPs are likely enriched in both iron and silica.

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S15a - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

On the Extended Transition Zone Beneath Ocean Basins

DOI: 10.57757/IUGG23-3598 - LINK

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In the last 10 years, global seismic tomographic models have shown that some subducting slabs pond in the extended upper mantle transition zone (ETZ, between 660 and 1000 km depth), as do most "fat" plumes that originate at the core-mantle boundary. These plumes extend quasi-vertically across the lower mantle, but have more complicated pathways in the upper mantle, where they are more difficult to resolve, since these plumes become thinner, likely due to a lower ambient viscosity. Recent results from full waveform tomography in the Atlantic and Indian Oceans show a variety of behaviors in the ETZ, with plumes meandering towards hotspot volcanoes at the earth's surface, and in the process, ponding at different depths in the upper mantle. Rarely does a plume extend vertically into the deep mantle directly beneath a hotspot. This is also the case beneath some well resolved continental plumes such as Yellowstone.

I will review these results and their geodynamic significance. In particular, I will discuss evidence for secondary scale convection across the ETZ in ocean basins, with cells aligned with absolute plate motion and a periodicity of ~2000 km. Combining evidence from seismic tomography and the analysis of meso-scale geodetic signals in the Pacific Ocean suggests the presence of lenses of partial melt atop the 410 km discontinuity, in the upwelling limbs of the secondary scale convection, likely due to dehydration melting.

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S15a - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

Examination of double seismic discontinuities at the base of the mantle transition zone beneath the northern Japan

DOI: 10.57757/IUGG23-3987 - [LINK]

Keiko Kuge[1]
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While the 660 km discontinuity at the base of the mantle transition zone is believed to be caused by a phase transition of the olivine system, multiple seismic discontinuities around 660 km have been found by using reflected and converted seismic waves, for example, beneath Mariana (Tibi et al., 2007) and Tonga (Zang et al., 2006). Since the multiple discontinuities can be associated with phase transitions of the non-olivine system in the mantle, the appearance and spatial extent of the multiple discontinuities are important for understanding the nature of the mantle.

Near the northeastern edge of China, double or multiple seismic discontinuities at the base of the mantle transition zone were indicated by the receiver function studies (Niu and Kawakatsu, 1996; Sun et al., 2020). However, the spatial extent to the east is not known. This study examines P waves triplicated by discontinuities around 660 km beneath the northern Japan where is located in the east of the previously indicated double discontinuities. The Japanese seismic stations recorded the P waves from deep-focus earthquakes in the northern Japan Sea and southwestern Sea of Okhotsk. A clear triplication of P wave from an earthquake appears in a similar manner to iasp91. In addition, the following signals are observed in vertical components, which might be the manifestation of another triplication. The series of P wave are considered to transverse the bottom of the mantle transition zone that is significantly below and away from the descending Pacific slab.

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S15a - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

Detection of sharp upper mantle discontinuities across North America: Silencing sediment reverberation and crustal multiples

DOI: 10.57757/IUGG23-0163 - LINK

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P-to-S receiver function (Ps-RF) is an effective approach to imaging sharp velocity discontinuities. However, when applied to continental-scale lithospheric imaging, it faces two fundamental challenges that cause significant signal distortion: (1) high-amplitude sediment reverberation that could completely mask conversion phases, and (2) crustal multiples that arrive at similar time window as mantle discontinuities, and thus complicate the interpretation of imaging results. Overcoming these difficulties and obtaining an improved mantle image of the continental United States is the goal of this study. We first apply a recently developed data-driven approach, using autocorrelation and homomorphic analysis, to teleseismic data recorded by Earthscope USArray Transportable Array (TA) to identify potential contamination from sediment reverberations. This technique does not require a-priori knowledge of the elastic structure of the reverberant layers. A frequency domain resonance removal filter, whose parameters are appropriately tuned by the seismic data, is then applied to stations with strong reverberation signatures. We then apply a selective sparse non-linear Radon filter to eliminate crustal multiples from the Ps-RF. The key idea emphasizes stable decomposition of noisy data-domain RF images into their underlying wavefield contributions in the radon domain by imposing sparsity-promoting constraints. The proposed methods are currently being applied to ~680,000 events, where we anticipate providing improved constraints on the composition, hydration, or change in the anisotropic signature that best characterizes seismic discontinuities beneath the contiguous US.

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hydration, or change in the anisotropic signature that best characterizes seismic discontinuities beneath the contiguous US.

S15b - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

A kilometre-scale mantle basal layer? An assessment using seismic data of different frequencies

DOI: 10.57757/IUGG23-2248 - [LINK]

Stuart Russell[1], *Jessica Irving*[2], *Lisanne Jagt*[1], *Sanne Cottaar*[1]
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The region atop the core-mantle boundary (CMB) contains numerous heterogeneities that have been imaged using seismology. Ultra-low velocity zones (ULVZs) are extremely slow seismic anomalies that are tens of kilometres thick. Their origins are not known, but possibilities include iron-enrichment, the presence of partial melt, or both. It is also possible that ULVZs are part of an extensive layer of low seismic velocities that, being too thin to be robustly detected, has thus far eluded detection.

We test the visibility of such a layer to seismic data at different wavelengths, utilising both high-frequency core diffracted waves and normal mode centre frequencies. Using forward modelling we test the effect of a thin slow layer atop the CMB, finding that PKKPdiff, which diffracts three times at the CMB, is incredibly sensitive to such a structure, as are the centre frequencies of some normal modes. We compile datasets of PKKPdiff observations and normal mode centre frequencies and find that not only is a thin seismically anomalous layer compatible with observations, but that both data types are better fitted by the inclusion of an approximately single kilometre thick global layer with ULVZ-like velocity reductions. Nevertheless substantial trade-offs, both between different seismic parameters and the thickness, do remain.

Our results cannot uniquely constrain the origin or composition of such a layer, however the possible presence of this structure atop the CMB could have profound consequences for core-mantle chemical interaction, core-mantle coupling, CMB heat flow and convection in both the mantle and outer core.

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S15b - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

The topography of the 660-km discontinuity beneath the Kuril-Kamchatka revealed by dense SdP observations and its geodynamic significance

DOI: 10.57757/IUGG23-3706 - LINK

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The 660-km discontinuity (660) plays an important role in deep slab dynamics and mantle convection. Increasing numbers of seismic observations suggest controversial morphologies of the Pacific slab beneath the Kuril-Kamchatka located in the northwest rim of the Pacific Ocean, highlighting the poorly understood interaction of the slab and mantle discontinuities. Here we collect near-source SdP converted waves from a large dataset with several dense seismic networks and systematically image the new 660 topographic map around the Pacific slab beneath the Kuril-Kamchatka. We conduct detailed comparisons of the 660 depths and seismicity along some vertical cross sections. In comparison with the discontinuity depth in the IASP91 model, the 660 exhibits broad depressions up to 32–63 km with apparent downward deflections beneath the Kamchatka Peninsula and northern Kuril (region I), supporting slab penetration into the lower mantle; in contrast, the 660 depressions beneath southern Kuril (region II) are less than 21–28 km with a relatively flat configuration, implying a stagnating slab with possible hot entrained mantle materials and/or partial melts below it. We interpret these regional variations in the 660 topography as reflecting local low-temperature anomalies due to different slab morphologies associated with contrasting subduction modes. We suggest compound effects of pressure-driven mantle flow and trench retreat for inducing the inferred subduction mode change of the Pacific slab from region I to region II. Our results can provide direct seismic evidence for the 660 with slab-induced depressions and shed new light on the morphology and subduction dynamics of the northwestern Pacific slab.

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S15b - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

The upper mantle and the transition zone under Peru and Chile

DOI: 10.57757/IUGG23-3879 - LINK

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We analyse 22,504 receiver functions obtained from 1162 seismic stations from 10 permanent and 32 temporary networks in South America. This region has been affected by the interaction of the subduction of the Nazca slab, which has changed its geometry through geologic time, breaking up and leaving fossil remnants or bucking it up above the 660. The receiver functions complexity and the topography of the upper mantle discontinuities correlate with the interaction of the Nazca plate with the upper mantle and mantle transition zone, the presence of a remnant slab segment and the hydration due to the slab.

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S15b - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

Global observations of regional-scale discontinuities in Earth's upper mantle associated with thermochemical heterogeneity

DOI: 10.57757/IUGG23-1267 - LINK

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[2]New Mexico State University, Physics, Las Cruces, USA
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Earth's upper mantle is characterised by abundant seismic discontinuities, which influence global mantle convection. Their physical properties (depth, and reflectivity) provide insights into the spatial variation of temperature and composition. Here, we perform global seismic interrogations of regional-scale discontinuities at 300 km, 520 km, and 660 km depth, to identifying regions of compositional layering associated with impeded flow of material or efficient flux.

The global 660-km discontinuity marking the base of the mantle transition zone (MTZ) comprises two mineral phase changes of ringwoodite and garnet, and is typically invisible to PP-precursors. Its visibility is associated with high temperatures and a dominant garnet transition, which promotes upward transport of high temperature material. Better constraints on the 660 will therefore contribute to models of global circulation patterns.

Observations of the 300 km deep "X" discontinuity are sporadic, typically beneath continental regions and subduction zones. Its presence is attributed to mineral transformations within basalt-enriched material, thereby aiding the detection of stagnant slabs. Conversely, the 520, caused by the transition of wadsleyite to ringwoodite, is observed in a larger portion of the globe, displaying complex variability in its visibility, depth, and splitting.

Mineral physics modelling predicts that the seismic characteristics of these features are highly dependent on local thermochemistry. We combine seismic measurements from large global datasets to generate high resolution maps of the discontinuities. We interpret our results in the context of recent thermochemical maps for the MTZ, to obtain new insight into chemical segregation and stagnation of convecting material in the upper mantle.

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S16a - Earthquake Source Mechanics

Modes of long-term forearc deformation in the Northern Chile subduction zone from earthquake source mechanisms

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Subduction zone forearcs deform transiently and permanently due to the frictional coupling with the converging lower plate. Transient stresses are mostly the elastic response to the seismic cycle. Permanent deformation is evidenced by forearc topography, upper plate faulting, and earthquakes; its relation to the megathrust seismic cycle is debated. Here we study upper plate seismicity in the northern Chile subduction zone as a proxy for forearc brittle deformation. We find that seismicity is distributed unevenly and a dramatic increase correlates with the onset of a change in subduction obliqueness. Earthquakes in the South American crust show a remarkably homogenous trench-parallel, compressional stress field. Earthquake fault mechanisms are dominated by trench-perpendicular thrusts. Further inland, where the lower plate becomes uncoupled, the stress field is more varied with a compression direction approx. convergence parallel. The stress regime above the plate-coupling-zone, almost perpendicular to the plate convergence direction, may be explained by a change in subduction obliqueness due to the concave shape of the plate margin, which we demonstrate by investigating inter-plate earthquake slip vectors. From these, we derive a strain rate and compare it to one derived from upper plate earthquakes and geological time-scale shortening. Based on the distribution of the type of faulting we investigate the trench-perpendicular stress field with a force balance model taking into account gravitational stresses and the traction along the megathrust. The observed deep strike-slip earthquakes, expression of trench-perpendicular tension, require the deepest extent of the megathrust to be very weak.

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S16a - Earthquake Source Mechanics

Evidence of phase transformation of material within subducting slab in Hindukush-Pamir Himalaya region: A paradigm shift through b-value mapping

DOI: 10.57757/IUGG23-0013 - LINK

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The Hindukush- Pamir Himalaya region is one of the most active orogenic regions of the world having complex and peculiar tectonics, experienced several large to great earthquakes in the past. The area 25^0-40^0N and 65^0-85^0E, have been considered for b-value mapping. A homogeneous and complete seismicity database with cut-off magnitude Ms$\geq$ 4.0 has been prepared for the period 1853 to Oct. 10, 2005 from different existing sources. The a and b-values for the study region G-R relationship (Log N = a – b M) has been estimated. In order to map a and b-values the most complete seismicity database for Ms $\geq$ 4.0 during the period 1963 to Oct. 10, 2005 has been used. The a and b-value has been estimated by maximum likelihood method using spaced grids of 0.50 X 0.50 with 50 to 200 nearest earthquakes and considering spatial variation of Mc. The spatial variation of ‘a’ value ranges from a low of 5.20 to as high as 8.51 and b-value ranges from a low of 0.7 to as high as 1.5. The Low b- value regions infer as the growing stress regime releasing larger magnitude earthquakes while high b value indicates increased crustal heterogeneity and low stress buildup with continued stress release through numerous smaller magnitude earthquakes. The b value varies as a function of depth suggest a random distribution of low to high b-value showing the heterogamous crustal structure beneath it. However, in subduction zones which may indicates a phase transformation of material in subducting slab.

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Seismogenic characterization of Colombian Caribbean and its implication over regional tectonics

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The uncertainties on the calculation of routine seismic event localization at the convergence zone between the Caribbean Plate and Norandean Block are mainly caused by general procedures adopted by seismic agencies such as Red Sismológica Nacional de Colombia (RSNC) and United States Geological Service (USGS). Here we improve the characterization of seismogenic sources of the Colombian Caribbean by estimating and using local velocity models, performing robust regional moment tensor inversion and embodiment of additional geophysical inputs. The sources are spatially constrained as superficial (0-30 km), intermediate (30-70 km) and deep (>70 km). Most significant seismicity in the South American Plate is given by the North Romeral fault (especially along the eastern part of this system), Sierra Nevada de Santa Marta (SNSM), northern Bucaramanga Nest and the Panama-Choco Arc. Furthermore, a seismic cluster indicating the interaction between the fault systems of Santa Marta-Bucaramanga (SMB) and Oca-El Pilar (OP) is proposed at its offshore intersection point. The effect of complex seismogenic geometry controlled by the convergence and interaction of three tectonic plates is investigated by means of the analysis of Wadati-Benioff zones through seismic profiles across the study area. For the northernmost part, the Moho's expression changes due east, and it is described here as a shallowly dipping, ductile and incipient subduction not related to the Paleo-Caribbean Plate that is found southward and striking E-W. In the western part, the "Nazca - Norandean Block - Caribbean Plate" triple point interaction undergoes strong compressional movements as well as tectonic uplifting.

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S16a - Earthquake Source Mechanics

A detailed analysis of stress variations of the Gulf of Gökova and its surroundings

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The Gulf of Gökova is located in one of the most substantial horst-graben systems in Western Turkey, generating significant seismic activity owing to the development of several complex features alongside The Gökova Fault Zone (GFZ) due to plate motions along the Aegean subduction zone. The region has experienced significant seismic activity both in historical and instrumental periods. With an estimated size of M6.8 and an intensity of IX, the oldest documented event took place in 412 BC near Kos Island. Notably, following the 2017 Mw6.6 Bodrum earthquake, the complicated tectonic structure of the area was studied extensively and highly debated indicating the necessity of a detailed study of the active tectonics of the region.

In this study, source parameters of 140 earthquakes (M>3.0) that occurred between 2006-2022, in and around the Gulf of Gökova (located between 36.5°-37.5°N and 26.8°-29°E), are calculated to be further implemented in stress tensor inversion. The region is split into six sub-regions concerning depth, focal mechanism variations, and active tectonic features and analyzed individually. In the northern part of the gulf, including the Gökova and Muğla faults, the maximum principal stress indicates normal faulting, with a counter-clockwise motion from NE-SW to NW-SE. The southern part of the gulf exhibits scattered seismicity and diverse tectonic elements, including Datca, Bozburun, Selimiye, and Taşlıca faults. Hence, the observed principal stresses indicate a transformational structure that concurrently induces normal and strike-slip faulting.

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S16a - Earthquake Source Mechanics

Source characteristics of the earthquakes around the south part of the Kuril trench

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The corner frequency of the seismic source spectrum and the stress drop are crucial to predict accurate strong ground motion. These parameters depend on other parameters, such as the focal mechanism, depth, and focal region. A high occurrence probability is estimated for a megathrust earthquake along the Kuril trench from off Tokachi to off Nemuro, Hokkaido, Japan. We tried to determine the corner frequency and stress drop using M>5 earthquakes to improve the accuracy of the strong motion prediction of megathrust earthquakes in this area. Using spectral inversion analysis, we separated the seismic source characteristics, propagation path, and site amplification from the strong ground motion records of middle to large earthquakes in the southern Kuril trench. The site amplification factor of HKDH05, a rock site, is a constraint condition. We obtained the source characteristics of 159 earthquakes and the site amplification characteristics of the 190 sites. The Qs value for the attenuation characteristics in the fore-arc region of the volcanic front is consistent with previous studies, and the site amplification characteristics are also comparable to existing values from previous studies. Regarding the seismic source spectra, we fit the omega-squared model and obtained the corner frequency for each earthquake. The short-period levels extracted from the fitted source spectra of intraslab earthquakes are approximately twice as high as those of interplate earthquakes. The stress drops have a weak correlation with the focal depth and vary depending on the focal region, with values off Nemuro being larger than those off Tokachi.

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Identification of seismogenic structures in Witwatersrand Basin, South Africa - About identifying active and potentially seismic structures.

DOI: 10.57757/IUGG23-2881 - LINK

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Identification of seismogenic structures in Witwatersrand Basin, South Africa

S. Myendeki[1], V. Midzi[1], J.van Bever Donker[2]

1. Council for Geoscience, South Africa, smyendeki@geoscience.org.za
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Earthquakes are not always directly linked to visible structures; some structures are deep and blind. This study will demonstrate an interdisciplinary techniques approach; using ArcGIS to map seismic events, high-resolution Airborne Magnetic data to map deep-seated lineaments, and LiDAR (a high-resolution airborne topographic mapping tool) to identify elusive surface expressions of active faults.

The seismicity clusters being investigated are situated in the West Rand within the Witwatersrand Basin. The West Rand region in South Africa is known for deep-level mining operations. The seismicity activity dates back to the early 1900s and has continued intermittently to the present day. The thousands of events found to be present in the region are generally suggested to be mining related. However, some investigations have indicated that seismicity is a mixture of natural, triggered, and mine-related events.

The bigger events (i.e. M $\geq$ 3.0) often occur on geological structures and result in extensive damage underground and on the surface. Geological structures that are under high stress or are susceptible to destabilization due to mining may be more susceptible to larger seismic events.

The identification of seismogenic structures, especially ahead of mining activity can contribute much towards creating a safe mining environment as well as more realistic seismic hazard assessment studies. Thus, this study aims to identify seismogenic structures associated with earthquake locations.

Identification of seismogenic structures in Witwatersrand Basin, South Africa

S. Myendeki[1], V. Midzi[1], J.van Bever Donker[2]

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S16b - Earthquake Source Mechanics

Hamiltonian Monte Carlo Inversion of Groningen Earthquake Sources

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Located in the northern part of the Netherlands, the Groningen gas field is one of the largest gas fields in Europe and is known as an earthquake-prone area for induced seismicity. The prolonged gas extraction in the area have been pointed out as the main cause of the earthquakes. While many studies have indicated that the earthquakes mainly originated from the reservoir layer, several latest studies show the possibility that the majority of the earthquakes nucleated just above the reservoir layers. In this study, we investigate the possibility of the latter hypothesis as well as the main mechanisms of the Groningen earthquakes. To do that, we applied an efficient probabilistic algorithm, the Hamiltonian Monte Carlo algorithm. The aim is to estimate ten earthquake source parameters. Those are the moment tensor (six components), hypocenter (three coordinate components), and origin time. Having the probabilistic estimates of the parameters, we then compare them with the reservoir map of Groningen to asses the pre-described hypothesis. We also used the fault map of the Groningen subsurface to see the match between the mechanisms we obtained and the orientation of the mapped subsurface faults. Additionally, we also compare our results with several related research from the area. In the end, we found that there is indeed a high probability of earthquakes nucleated just above the reservoir level, with the mechanisms mainly triggered by the movement of the mapped subsurface faults.

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A Bayesian double source approach for landslides and earthquakes characterization

DOI: 10.57757/IUGG23-2765 - LINK

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The characterization of a seismic source is crucial to understand seismogenic processes. Simplified source models, e.g., a moment tensor, may not be suited for certain physical processes, such as landslides or complex earthquake ruptures. We propose here a double source model to reproduce landslide processes, with two opposite oriented forces representing the detachment and impact of a sliding mass. A double source model is also suited to characterize complex earthquake ruptures, as it allows modeling the failure of two patches along a single or on two different faults. The inversion for a double source is implemented in a Bayesian bootstrap-based probabilistic inversion scheme with uncertainty estimation for all parameters. In the case of landslides, the source is described by two independent single forces and earthquakes are described by two dependent double-couples. The double single-force model includes 16 free parameters and the double double-couple model includes 18. Here we show the results obtained in the analysis of three different landslides (Val Bondasca-Switzerland 2017, Anak Krakatoa-Indonesia 2018 and Uttarakhand-India 2021) and two complex earthquake ruptures (Alaska 2018, South Sandwich islands 2021). Our findings show that our approach can resolve the landslide geometry and slope orientation. For the case of earthquakes, we were able to resolve the focal mechanism along two faults, which were active during the Alaska 2018 earthquake, as well as the time delay and orientation of the South Sandwich doublet in 2021.

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ISC-PPSM: Assessing moment tensor resolution, and addressing shallow earthquake depth resolution

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We present a new technique to assess the moment tensor, source time function (STF) and depth of an earthquake, along with a full estimate of the uncertainties in each of these parameters. This methodology is being applied at the ISC (International Seismological Centre) to construct a new catalogue of earthquake point source models, referred to as ISC-PPSM (International Seismological Centre – Probabilistic Point Source Models).

We employ a Bayesian inversion strategy to produce an ensemble of earthquake point source models that satisfactorily describe the P- and SH-waves observed tele-seismically at global broadband seismic stations. The methodology builds on the techniques proposed by Stähler & Sigloch (2014, 2016). Here we explore several ways of parameterising the earthquake STF, including describing the STF as a set of weighted harmonic functions, and describing the STF as the sum of multiple Gaussian spikes.

ISC-PPSM is applied to moderate magnitude (5.5 – 7.2 Mw) earthquakes across the globe. As we jointly solve for the earthquake depth and STF, we can add new depth resolution to shallow (< 40 km depth) moderate magnitude earthquakes, where the depth phases become subsumed within the STF. Additionally, the Bayesian inversion strategy allows us to assess the range of earthquake moment tensors that can describe the observed waveforms for a given event. This allows is to go some way towards constraining the variability in moment tensors reported to the ISC for many events.

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S16b - Earthquake Source Mechanics

Scaling relations and variability of source parameters for shallow crustal earthquakes in Europe

DOI: 10.57757/IUGG23-3892 - LINK

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[3]European Center for Geodynamics and Seismology, European Center for Geodynamics and Seismology, Walferdange, Luxembourg

The source parameter, stress drop, is a key parameter estimating strong ground motion, as it controls the level of peak ground acceleration. Several studies have investigated source parameters for many regions by various methods and assumptions (e.g., Japan, Southern California, and central Italy). In this study, we apply a non-parametric spectral decomposition to isolate the source, site, and path contributions on the Fourier amplitude spectra (FAS) in Europe. We propose the two-domain regionalized attenuation models in the spectral decomposition to take into account the varying attenuation of two spatial domains along the Alps. We download all available data from 1990 to 2020 in Europe through the European Integrated Data Archive (EIDA) within the *stream2segment* software. The analyzed FAS are selected from 35.6 million recordings which contain 6,135 earthquakes recorded by about 1,600 stations. The final data includes the induced events in Groningen and Poland and some significant events in Italy which provide the opportunity to discuss the variation between induced and natural earthquakes. To derive comparable source parameters in such a large study area, we set one station, LLS (Linth-Limmern), in the Swiss network as a reference site to obtain the corrected source spectra. Finally, we fit the source spectra with a standard ω^2-model. The resulting stress drop shows a positive correlation with earthquake magnitude in the magnitude range of 2 to 4.5 and a constant value for larger magnitudes (M>4.5).

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S16b - Earthquake Source Mechanics

Systematic exploration and characterization of moderate magnitude seismicity in scarcely instrumented places

DOI: 10.57757/IUGG23-4630 - LINK

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As a result of the uneven geographical coverage by seismic stations, the seismicity of a number of seismogenic areas (including oceanic ridges, but not only) is only known for large magnitude events exhibiting high-frequency arrivals. Besides affecting the completeness of the earthquake catalogues, this undetected seismicity may also have some specific source properties, in particular in terms of frequency content. The analyses of the global seismic wavefield (e.g. Ekström, 2006) reveal that large magnitude (above magnitude Mw5) exotic tectonic sources are very likely rare; at lower magnitudes, the detection of very-low-frequency earthquakes (VLFE) shows that such sources exist, but with a global abundance which remains today unclear.

Isolated places where a few regional broadband seismometers, usually from the global broadband networks (GSN, Geoscope, Geofon), are in operation since the 1990’s or 2000’s can be selected to exhaustively detect the seismicity of the last decades, at a threshold of Mw3.5-4. To do so, the present work proposes to match-filter the continuous records with the waveforms of all the known earthquakes, in order to search for events that are similar at long periods (e.g. 20-50s) but may differ at short periods. This study will present results from a few areas of the world where such a method has been implemented.

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Source mechanisms of the 2020 volcano-tectonic swarm on the Reykjanes Peninsula (Iceland) by probabilistic moment tensor inversion

DOI: 10.57757/IUGG23-1942 - LINK

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In this study, we analyze the 2020 earthquake swarm on the Reykjanes Peninsula by moment tensor inversion in order to improve our understanding of the seismogenic processes and their relation with magmatic and tectonic activities. The densified seismic monitoring operational during the study period provides a unique dataset for the seismic sequence preceding the 2021 Fagradalsfjall eruption. We perform full moment tensor (MT) inversion for 85 earthquakes with magnitudes Mw > 2.5 using a probabilistic approach. For the first time, we attempted to integrate DAS data into the MT inversion. Focal mechanisms exhibit predominantly strike-slip faulting with a few normal faulting events and are overall compatible with the regional tectonic regime. Earthquake foci are shallow with an average depth of 3 km. We estimate robust, significant, positive isotropic components contributing up to 15% to the moment release. We hypothesize that the origin of such significant non-double-couple (non-DC) components may be attributed to volume changes accompanying the surface uplift and rifting processes in the region. Our study demonstrates that non-DC earthquake source components can be monitored prior to eruption and potentially, their identification may be used as indicator for magma intrusion in the shallow crust.

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S16c - Earthquake Source Mechanics

The 2021 Vienna Basin seismic sequences: Insights from earthquake relocation and moment tensor inversion

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Two seismic sequences occurred between March and April 2021 near Neunkirchen and Gloggnitz, about 50 km from Vienna, Austria. The mainshocks epicenters of both series are located around 15 km apart from each other.

According to the Austrian Seismological Service at GeoSphere Austria, the Neunkirchen sequence, which includes the two largest earthquakes of both series (Mw 4.0), started on March 11th, 2021 and finished on May 12th, 2021. Over two months, 245 earthquakes, with local magnitudes ranging from -0.5 to 4.6, were recorded.

The Gloggnitz sequence started on April 1st, 2021, and continued until May 8th, 2021. Here, a total of 65 earthquakes were detected and located. The local magnitudes of this seismic sequence ranged from -0.3 to 3.8 and depths varied between 4 and 7 km.

Taking advantage from the high density of seismic stations (Geosphere Austria, AlpArray, and neighboring networks), we relocated the seismicity and performed centroid moment tensor inversions for the largest earthquakes of the series. Results highlight some peculiarities of these two seismic sequences, which only affected small seismogenic volumes along or next to known fault structures. The heterogeneity of focal mechanisms of events in close proximity suggests the activation of different faults at slightly different depths. To include smaller events in the analysis of activated faults, we further investigate waveform-similarity based event clusters.

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S16c - Earthquake Source Mechanics

Seismic source analysis for recent seismicity at Mt. Vesuvius (southern Italy): preliminary results from a full waveform inversion approach

DOI: 10.57757/IUGG23-2721 - LINK

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The detailed analysis of volcanic seismicity can allow the identification of the processes occurring in a volcanic system and obtain information about its state and evolution. In the last decades, the seismicity of Mt. Vesuvius has consisted mainly of volcano-tectonic (VT) seismic events, with an average rate of some hundreds of earthquakes per year with magnitudes between −1.0 and 2.5, located up to 6-7 km below sea level (b.s.l.). Unusual low-frequency (LF) seismicity has also been observed, localized at a depth of 5-7 km. Previous seismic source analyses applied conventional methodologies based on first pulse characteristics, which are difficult due to high background noise, low magnitude and emergent first arrivals. To overcome these challenges, we analyze here the Mt. Vesuvius seismicity over the past 20 years by using a robust probabilistic seismic source inversion tool. This methodology provides the results in terms of moment tensor solutions estimated by using seismic waveforms and waveform attributes. In agreement with previous studies, two clusters of seismicity are clearly evidenced, both in terms of depth (0-4 km and 5-7 km b.sl. for VT and LF events, respectively) and frequency content (5-15 Hz and 2-6 Hz, respectively). Our preliminary results show that: a) the probabilistic approach for the whole waveform inversion provides acceptable results even for small magnitude earthquakes, and b) both seismicity clusters show strongly heterogeneous focal mechanisms, confirming past literature studies. We attribute the latter result to a highly heterogeneous stress field beneath Mt. Vesuvius.

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S16c - Earthquake Source Mechanics

Fault plane identification of the September 2021 Mw 5.9 Woods Point earthquake

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Fifty broadband, research-grade seismic stations housed in schools are operated by the Australian Seismometers in Schools (AuSIS) network across Australia. Using only data from the AuSIS network we present the feasibility of identifying the fault plane of moderate earthquakes on the Australian continent. We examine the fault plane of the September 2021, MW 5.9 Woods Point earthquake which happened roughly 130 km northeast of the Melbourne metropolitan area. We estimate the hypocentre and the centroid-moment-tensor to differentiate the fault plane from the auxiliary plane in the focal mechanism. In order to simulate seismic arrivals and full waveform data, we test a variety of 1D models and a 3D Earth model. The centroid-moment-tensor is obtained from full waveform modelling by grid search across a set of trial sites around the hypocentre. The hypocentre is resolved using P and S-wave arrivals in a probabilistic framework. Our model indicates that the main shock ruptured the depth of 15±4 km, with a strike-slip mechanism striking 348º North on a nearly vertical plane. The high double-couple (DC) percentage of this event suggest a simple rupture that propagated from the south (hypocentre) toward the north (centroid) while remaining underground. This indicates that the causative fault ruptured deeper parts of the crust which might be different to the previously identified shallow, NW-SE striking faults of the region. The P- and T-axis inferred from our fault model are clearly aligned with the maximum horizontal crustal stress in the region.

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Coseismic faulting complexity of the 2019 Mw5.7 Silivri earthquake in the central Marmara seismic gap, offshore Istanbul

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The submarine Main Marmara Fault is overdue for an M>7 earthquake in the direct vicinity of the Istanbul megacity and is the only segment of the right-lateral North Anatolian Fault Zone that has not been activated since 1766. On 26 September 2019, an Mw5.7 earthquake occurred offshore Silivri (west of Istanbul), stimulating discussions on a future major earthquake. The predominant faulting style for this pending earthquake remains enigmatic. In this study, we investigate the coseismic rupture evolution of the 2019 Silivri earthquake and decipher the multi-type-faulting aspects by a nonstandard approach. The event was dominated by a large compensated-linear-vector-dipole component, of about -50% that we interpret as a consecutive strike-slip and thrust double-couple episode, closely collocated in space and time. Due to local variations of the fault geometry at the eastern boundary of the Central Basin, crustal shortening and related thrust-faulting are expected. A striking observation is the almost synchronous occurrence of both faulting types during a single earthquake. The earthquake complexity here is reported for the first time in the Sea of Marmara region and has to be considered in future rupture scenarios of an expected M>7 event, with subsequent consequences for tsunami hazard and risk.

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The 2022 MW 6.0 Gölyaka-Düzce earthquake: a medium size earthquake in a fault zone early in its seismic cycle

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On November 23rd 2022, a M_W 6.0 earthquake occurred in direct vicinity of the M_W 7.1 Düzce earthquake that ruptured a portion of the North Anatolian Fault in 1999. The M_w 6.0 event was attributed to a small fault portion of the Karadere segment that did not rupture during the 1999 sequence. We analyze the spatio-temporal evolution of the M_W 6.0 Gölyaka-Düzce seismic sequence at various scales and resolve the source properties of the mainshock. Modelling the decade-long evolution of background seismicity of the Karadere Fault employing an Epistemic Type Aftershock Sequence model shows that this fault was almost seismically inactive before 1999, while a progressive increase in seismic activity is observed from 2000 onwards. A newly generated high-resolution seismicity catalog from 1 month before the mainshock until six days after created using Artificial Intelligence-aided techniques shows only few events occurring within the rupture area within the previous month, no spatio-temporal localization process and a lack of immediate foreshocks preceding the rupture. The aftershock hypocenter distribution suggests the activation of both the Karadere fault which ruptured in this earthquake as well as the Düzce fault that ruptured in 1999. First results on source parameters and the duration of the first P-wave pulse from the mainshock suggest that the mainshock propagated eastwards in agreement with predictions from a bimaterial interface model. The M_W 6.0 Gölyaka-Düzce represents a good example of an earthquake rupture with damaging potential within a fault zone that is in a relatively early stage of the seismic cycle.

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Normal and thrust faulting earthquakes triggered by magma intrusion at the Mid-Atlantic ridge

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A large seismic swarm affected the North Mid-Atlantic ridge between September and November 2022, with an outstanding seismicity rate and a cumulative moment equivalent to a magnitude Mw 6.3. We performed a detailed seismological analysis using regional, teleseismic and array data to reconstruct the spatiotemporal evolution of the seismicity. Combining template matching, relative location and full moment tensor inversion, we identify that most seismicity was located in a narrow band along the ridge, with typical normal faulting mechanisms. However, some of the latest and strongest events occurred up tp 25 km off the ridge axis, with thrust mechanisms that are atypical at mid-ocean ridges and inconsistent with the extensional tectonics. Seismicity also present a clear migration pattern, propagating over ~60 km from North to South, with the thrust mechanisms only occurring in the late phase of the swarm and only in the central-southern section. We hypothesize a magmatic intrusion as driver of the seismicity, with a vertical dyke first propagating southward, accompanied by normal faulting earthquakes, and then thickening, to produce a stress perturbation able to trigger thrust earthquakes on pre-existing structures on the side of the dike. The 2022 unrest provides evidence for sporadic spreading accompanied by large swarm episodes driven by magma intrusions at the mid-ocean ridge.

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S16d - Earthquake Source Mechanics

Probing earthquake triggering by static and dynamic stresses at Axial Seamount

DOI: 10.57757/IUGG23-3229 - LINK

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Since 2015, when a cabled observatory was first set up on Axial Seamount, >150,000 earthquakes have been located within a 25 km^3 block of crust. The volcanic system has also experienced the passage of seismic waves from >120 large remote earthquakes and periodic tidal loading. Therefore, it represents a unique laboratory for us to probe how earthquakes respond to static and dynamic stress changes. We find that the seismicity rate increases while the b-value decreases (larger proportion of large events) systematically with increasing tidal stress. The stress dependence of seismicity rate conforms to triggering theory over the whole tidal stress range, demonstrating that there is no triggering stress threshold and stress shadowing is simply a continuous function of stress decrease. We also observe statistically significant episodes of dynamic triggering for ~11% of large remote earthquakes. However, while some coincide with changes in permeability estimated from changes in the tidal phase lag of hydrothermal vent temperature, others are not. Therefore, permeability change is likely not the only mechanism underlying dynamic triggering of earthquakes.

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Foreshocks preceding moderate earthquakes in Western Yunnan, China

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Although the physical mechanism of earthquake nucleation processes is under debate and it is still challenging to distinguish foreshocks during an ongoing seismic sequence, foreshocks may still provide unique and valuable information for earthquake nucleation process. Investigating the temporal and spatial evolution of foreshock sequences with high resolution and monitoring *b*-values in real time may shed light on these key issues. Here we investigate a series of earthquake sequences in western Yunnan, China, where a number of moderate to strong earthquakes were well recorded by the newly established seismic network. To find missing earthquakes and build more comprehensive earthquake catalogs, we first carry out earthquake detection using the matched-filter detector. We use events in the standard catalog of China Earthquake Networks Center as templates to scan through continuous waveforms 3-6 months before and after the mainshock. We then estimate the *b*-value and its temporal changes based on the newly developed catalogs. An obvious reduction in *b*-values before the major earthquake was observed in both the 2016 Ms5.1 Yunlong and 2021 Ms6.4 Yangbi sequences. However, we didn't observe such a feature before the 2017 Ms5.1 Yangbi mainshock, showing spatial variations in the region. After the relocation of the detected earthquakes and deriving their source parameters including focal mechanisms and stress drops, we found that the foreshocks in western Yunnan exhibit mostly a cascading rupture manner, rather than indicating slow-slip driving nucleation of mainshocks.

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S16d - Earthquake Source Mechanics

Evidence of the ambiguous critical state transition from aseismic to seismic slip

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The idea that earthquake processes occur on a continuum from aseismic (stable sliding) to seismic slip (event nucleation) is not new, however the mechanisms causing any evolution between the two end-members is not fully understood. Possible mechanisms may relate to dynamic fault weakening, static stress transfer, the concentration of shear stress at the boundary of an aseismic region, some combination of these, or a mechanism we have yet to detect. Moreover, the detection of aseismic processes is inherently difficult, adding to the challenges in detecting and understanding this evolution. Here, we investigate evidence for a critical state transition within the subsurface using data from several recent seismic sequences in western Canada. The first case investigates a potential change in seismic event rate following prolonged fluid injection at a water disposal well, suggesting that initial deformation in the subsurface related to the injection was aseismic. Twelve months into the injection program, a large change in the seismic event rate was observed, along with a change in the source characteristics of the events, suggesting a transition from dominantly aseismic to seismic slip. Another case investigates seismicity in a historically quiescent area where there is ongoing fluid injection. A M5.3 mainshock was followed by an unusual aftershock sequence, which showed limited evidence of Omori-like decay, and instead, remained persistent. We investigate these sequences using an array of techniques including ambient seismic noise, repeating seismicity and the identification of tremor-like signals to determine whether there is evidence of a critical state transition at depth.

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S16d - Earthquake Source Mechanics

Direct estimation of the fault slip of short-term slow slip events from GNSS data using deep learning

DOI: 10.57757/IUGG23-4908 - LINK

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In this study, we aim to develop a deep-learning method to monitor spatio-temporal evolutions of short-term SSEs based on a dense GNSS network. We theoretically create two types of noiseless three-dimensional (3D) deformation data assuming 272 subfaults in western Shikoku, southwest Japan; 16 subfaults along the strike multiplied by 17 subfaults along the dip. One is deformations at 95 GNSS stations, and the second is those at 900 virtual stations which are regularly located over the target area. We tailor two supervised-learning models to estimate the slip area and the slip amount of SSE by learning those deformation images as input data. Nakagawa et al. (2021, Fall Meeting in Geodetic Society of Japan) showed that the model trained with GNSS stations estimated SSEs with 91.8% variance reduction (VR) while the other model achieved 98.3% VR. We concluded that this difference in estimation accuracy is contributed to the dissimilarity between input deformation images. Therefore, we newly implement Model-supervised Interpolation (MSI) approach to overcome this problem. MSI successfully reproduces the deformations at 900 virtual stations only from the deformations at 95 GNSS stations with 97.4% VR although nearly half of the target area is located on the offshore region. Additionally, a model trained with deformation images predicted by MSI improves the VR of the slip estimation by 0.5%.

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S16e - Earthquake Source Mechanics

The complex 3D multi-segmented rupture of the 2014 Mw 6.2 Northern Nagano Earthquake revealed by high-precision aftershock locations

DOI: 10.57757/IUGG23-3482 - LINK

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Recent estimates of the rupture scenarios of moderate-to-large earthquakes highlights the need of incorporating segmented fault surfaces into seismic hazard models rather than individual, planar ones. The 2014 Northern Nagano earthquake sequence provides an opportunity to rethink the fault system geometrical complexities of the Itoigawa-Shizuoka tectonic line, one of the most inland active faults in Japan, and their impact on the fault rupture nucleation and development. For this study we used continuous records of 37 seismic stations to detect and locate 2500 events that occurred from 1st October 2014 to 31 December 2014. By refining the automatic arrival time picks, based on the cross-correlation and the hierarchical clustering, we relocated the earthquake hypocenters with the double-difference location and a three-dimensional (3D) velocity model. We obtained a high-quality earthquake location catalog and the composite focal mechanisms which served for constraining the 3D geometry of the segmented fault system. We found that the early aftershocks are distributed along two sub-parallel, NNE-SSW striking, en-echelon, left-stepping fault segments and analyses on the spatio-temporal evolution of fault activation suggest that the rupture propagates in a clockwise direction, involving first the shallow northern portion of the segmented fault system, then the deeper northern portion of it, and finally the deeper and the shallower parts of the southern portion. Results suggest that a relationship exists between the rupture mechanism and the 3D segmented fault geometry. This relationship between initial structure of the segmented fault controls the earthquake rupture becomes crucial to assess reliable scenarios in seismic hazard.

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S16e - Earthquake Source Mechanics

Development of the simultaneous estimation method of slip distribution and its correlation length based on the assumption of self-similarity

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Earthquake simulations, geodetic and seismological data analyses, and field surveys of fault outcrops indicate that the slip distribution on the coseismic fault is self-similarity. This characteristic can be used for fault slip estimation as prior information for the regularization of an ill-posed problem. In this study, we introduced the characteristic using the von Karman autocorrelation function and developed the method to simultaneously estimate the fault slip and its correlation length, which has been treated as a hyperparameter from the ground displacement. The method was constructed based on Bayesian inversion using Hamiltonian Monte Carlo to evaluate parameters' uncertainty quantitively. We conducted numerical experiments using a random slip distribution whose correlation length is assigned to validate our method. Under the assumption of a dense observation network, the input slip and the correlation length were retrieved correctly. Furthermore, the experiment assumed that the observations are distributed at only the fault's down-dip side. As a result, although, the longer correlation length has been explored than the result under the dense observations, its posterior distribution peaked near the assumed value. This presentation will also show the results of an application to the 2016 Kumamoto earthquake (Mw 7.0). In addition, we will discuss an application for a numerical test of a megathrust in the Nankai trough subduction zone, which has a more realistic, 3D-distributed fault system.

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S16e - Earthquake Source Mechanics

Reconstruction of slip distributions on multiple faults with applications to the 2016 kumamoto MW7.0 earthquake

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Slip inversion is essential to understand source mechanics of earthquakes. Problems of inverting for static/kinematic rupture from surface measurements have been almost always stated to be inherently non-unique in the seismological literature. Given the geometry of a fault and the displacement functions on the surface of the semi-infinite elastic medium, the slip function on the fault is defined by Fredholm integral equation of the first kind. We prove that Fredholm integral equation of the first kind for slip inversion is mathematically of a unique solution, theoretically implying that earthquake slip/rupture can be properly reconstructed. The inherent non-uniqueness issue of slip inversion in the seismological literature is not mathematically true but is practically caused due to lack of measurements. We propose a new inequality-constrained regularized inversion of slip distributions on multiple faults, which implements physically more general inequality constraints to accept more complex dislocation models and/or a combination of complex dislocation models and can be applied to a large earthquake involving multiple faults with different rake angles. It is a natural extension of positivity and the 45 degrees constraints by Olson/Apsel and Hartzell/Heaton. We apply the proposed method to the 2016 Kumamoto Mw7.0 earthquake with GEONET GNSS measurements. The inversion results of slips show that the 2016 Kumamoto earthquake is only of magnitude Mw6.6-6.7 and severe rupture takes place very shallowly on Hinagu and Futagawa faults, with the maximum slips of 4.81m on Hinagu fault and 7.89m on Futagawa fault, respectively, which may well explain the largest damage in Mashiki town.

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S16e - Earthquake Source Mechanics

Observational evidence of cascading earthquake rupture with hierarchical structure in the Tohoku-Oki region, Japan

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Over the past ~20 years, high-quality data have revealed the detailed behavior of repeating earthquakes in the Tohoku-Oki region, Japan, as a cascading rupture process within a hierarchical structure. This presentation reviews our recent studies that provide observational evidence for such hierarchical cascading ruptures. The centroid of repeating earthquakes can be precisely relocated using waveform correlation, while accurate relocation for the hypocenter is also possible using the P-wave first motions. Chang and Ide (2021) developed a method for the simultaneous relocation of hypocenters and centroids and applied it to three repeating earthquake sequences in the Tohoku-Oki region. They found that, although the hypocenter locations and the final slip distributions for large, medium, and small repeating earthquakes were largely determined, the combination of the hypocenter and centroid may be different, especially in the case of the Naka-Oki sequence, suggesting the limited predictability of the rupture process. The slip inversion of Okuda and Ide (2019a) also found that the slip of M~5 earthquakes in this group has an anisotropic spatial distribution in the subduction direction. The limited predictability suggests that two ruptures starting at different times from the same point may share a rupture on a small structure but subsequently exhibit different cascading behaviors. Okuda and Ide (2019b) first identified such a pair in the Naka-Oki sequence, and Ide (2019) confirmed the existence of many such pairs in the Tohoku-Oki region. We suggest that a hierarchical structure with limited predictability is ubiquitous on the plate interface in the Tohoku-Oki region.

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S16f - Earthquake Source Mechanics

Source function specialty in porous medium and its impact on forward and inverse problems in seismogeodesy

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The contribution of fluid in the rock to the response of the Earth to external/internal forces is more and more attractive. Poroelastic rebound is one of the mechanisms of the post-seismic deformation. However, the conventional source functions, i.e. discontinuities in displacements and stresses across the source level, are still being used in investigating the poroelastic rebound. The forward and inverse problems are of great importance in evaluating earthquake hazard and investigating source mechanisms, as well as interpreting the observed deformation of the Earth, where the key link is the Green's functions which are computed in terms of the dislocation Love numbers (DLNs). The DLNs are obtained by solving the boundary value problem, in which the source functions are crucial. According to the body force equivalence and the theory of poroelasticity, we derived the source functions of a point dislocation in a porous medium. We found that, except the well-known solid dislocation, there are an independent fluid dislocation (explosion source) and a solid-liquid coupling term in dislocation type of horizontally tensile fracture. We first modeled the displacements caused by a given porous fault and then invert the slip parameters of this fault, respectively, by pure and porous elasticity to show the impact of the differences in source functions in the two theories. The results show that the impact is significant. Therefore, we recommend that a new unknown of fluid displacement normal to the fault be included in the inverse problem to get a forward fault model for geodetic applications.

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S16f - Earthquake Source Mechanics

Numerical Modelling of Earthquake Cycles and Surface Topography Based on Navier-stokes Equations with Viscoelastic-plasticity Rheology

DOI: 10.57757/IUGG23-3767 - LINK

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Visco-elastic-plastic modelling approaches for long-term tectonic deformation assume that co-seismic fault displacement can be integrated over 1,000s-10,000s years (tens of earthquake cycles) with the appropriate failure law, and that short-timescale fluctuations in the stress field due to individual earthquakes have no effect on long-term behavior. Models of the earthquake rupture process generally assume that the tectonic (long-range) stress field or kinematic boundary conditions are steady over the course of multiple earthquake cycles. In this study, we develop a numerical framework that embeds earthquake rupture dynamics into a long-term tectonic deformation model by adding inertial terms and using highly adaptive time-stepping that can capture deformation at plate-motion rates as well as individual earthquakes. We reproduce benchmarks at the earthquake timescale to demonstrate the effectiveness of our approach. We then discuss how these high-resolution models degrade if the time-step cannot capture the rupture process accurately and, from this, infer when it is important to consider coupling of the two timescales and the level of accuracy required. To build upon these benchmarks, we undertake a generic study of a thrust fault in the crust with a prescribed geometry. We find that lower crustal rheology affects the periodic time of characteristic earthquake cycles and the inter-seismic, free-surface deformation rate. In particular, the relaxation of the surface of a cratonic region (with a relatively strong lower crust) has a characteristic double-peaked uplift profile that persists for thousands of years after a major slip event. This pattern might be diagnostic of active faults in cratonic regions.

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S16f - Earthquake Source Mechanics

Systematic understanding of slow and fast earthquakes in terms of the porosity evolution law

DOI: 10.57757/IUGG23-0621 - LINK

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We have constructed the systematic formulation treating both the slow and fast earthquakes using the 1D Burridge-Knopoff model and the interaction among the heat, fluid pressure, and porosity (Suzuki and Matsukawa, in prep.). By employing the assumption that the dependence of the model parameters such as bulk moduli on the porosity can be neglected (constant-parameter assumption) and a single block, we show that the thermal (pore-generation) effect is dominant for the fluid pressure change, the fast (slow) earthquake occurs. We extend the framework to that without these assumptions. When the porosity increases monotonically to the upper limit with increasing the slip, changing the upper limit for the porosity is important step to remove the constant-parameter assumption. We also consider multiple block model.

We first assume the large upper limit. We found that the slow-to-fast transition occurs, and several blocks slowly slip after the fast earthquake. This behavior is interpreted as a tremor, which is considered to consist of sequential slow earthquakes like low frequency earthquakes. When the upper limit of the porosity is reduced, the tremors are harder to occur because the pore generation effect on fluid-pressure change becomes smaller than that of the thermal effect. In this case, both fast and slow earthquakes occur several times, but their prediction is impossible. When the upper limit of the porosity is negligibly small, the pore generation effect is almost negligible, and only the fast earthquakes repeat.

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S16f - Earthquake Source Mechanics

On the frictional growth of fractures in the preparation phase of earthquakes

DOI: 10.57757/IUGG23-2078 - LINK

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We develop a simple fracture mechanics model for the stable growth of a penny-shaped shear crack under friction. We assume equilibrium between released strain energy and frictional energy and suggest a stability criterion that combines the tip stress intensity in fracture mechanics with the threshold criterion of frictional strength in a Coulomb failure approach. Fracture growth causes a slow but steady buildup of stress. On a larger fault, patches of increased shear stress may develop with the time to failure and the size of the patch depending on the background stress and the constitutive relations. The model predicts a self-regulating feedback loop that keeps stress intensity low until a strength threshold is exceeded at the point of high stress. At this point, instability occurs and a rupture nucleation phase may start culminating in a co-seismic rupture. The available fracture energy scales with the third power of the fracture length, while the slip on the fracture is a linear function of the fracture length.

The new model may explain how a slow preparatory phase transitions into rupture nucleation. It suggests that large earthquakes tend to develop on faults with intermediate stress levels. Faults with very low stress may not produce stress asperities and remain stable, while faults with very high stress tend to produce smaller earthquakes after a short preparation period.

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S16f - Earthquake Source Mechanics

Earthquake Sequence and Dynamic Rupture Modeling with Complex Fault Geometry

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[2]*China Earthquake Administration, Institute of Geology, Beijing, China*
[3]*Munich University, Department of Earth and Environmental Sciences, Munich, Germany*
[4]*Zhejiang University, School of Earth Sciences, Hangzhou, China*
[5]*Southern University of Science and Technology, Department of Earth and Space Sciences, Shenzhen, China*

Complex fault geometry can strongly affect earthquake rupture processes and slip sequences. I will first present our recent work on modeling earthquake and slow slip sequences on 3D fault surfaces, with applications to the Yingxiu-Beichuan fault (YBF) which hosted the 2008 Mw 7.9 Wenchuan earthquake in China and the Cascadia subduction zone. In the rate-and-state friction computational framework, earthquake and aseismic slip nucleate and propagate spontaneously under the influence of long-term tectonic loading and heterogeneous frictional properties. In particular, fault dip angle has a primary control on the along-strike segmentation of simulated earthquake and slow slip, in general agreement with observations from YBF and Cascadia. Fault local strike angle on the other hand strongly affects small-scale along-strike variations in the rupture speed and slip rate. Next, I will introduce a newly developed mixed-flux-based discontinuous Galerkin method and its application to simulate fully dynamic ruptures on complex fault geometries. The new method greatly reduces numerical dependence on mesh quality, and can accommodate complex fault properties including geometry, material heterogeneities and multi-physics mechanisms such as off-fault plasticity and thermal pressurization.

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S16f - Earthquake Source Mechanics

Physical interpretation of slow earthquake migration process based on a friction law

DOI: 10.57757/IUGG23-0024 - LINK

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I derive a quantitative relationship between various types of migrating slow earthquake phenomena and frictional properties of a rate and state dependent friction law. By assuming that local pore water in front of the migration drives rapid tremor reversal and is so local as to hold a constant stress drop, the application of the analytical solution to observational results suggests that(i) the temporal changes of observed migration speeds for the rapid tremor reversal could be explained by about 70% reduction of the effective normal stress; (ii) effective normal stress for the deeper extension of seismogenic segment in the western part of Shikoku is about 1.5 times greater than that in the central part. Applying rupture time delay between slow earthquake asperities for the duration longer than regular earthquake, I also conclude that (iii) the characteristic slip distance of rate-and-state friction for low-frequency earthquakes is roughly between 30 μm and 30 mm; (iv) the stress and strength drops of very low-frequency earthquakes is much smaller than 1 MPa.

References:

Ariyoshi, K. (2022). Extension of aseismic slip propagation theory to slow earthquake migration. *Journal of Geophysical Research: Solid Earth*, 127, e2021JB023800. https://doi.org/10.1029/2021JB023800

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S17a - Structure and evolution of the lithosphere in the circum-Mediterranean

Structure and dynamics of the circum-Mediterranean lithosphere and its controls on crustal deformation and magmatism

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The fascinating tectonic evolution of the Mediterranean region comprises subduction at numerous subduction zones, extension and seafloor spreading in back-arc areas, and convergence of major continents and smaller continental blocks between them. The active subduction of the Greater Adria block is a dominant feature of the central Mediterranean dynamics. AdriaArray, the ongoing major international experiment, has produced unprecedentedly dense seismic data sampling of the area. It brings into focus both its structure and dynamics and the methodologies for how to best use the abundant seismic and other data to determine the physical structure and dynamics of the lithosphere and underlying mantle.

The Mediterranean lithosphere is highly heterogeneous in its thickness, temperature and mechanical strength. This heterogeneity evolves with time and exerts controls on the intraplate magmatism and seismicity. Combined evidence from seismic anisotropy and the geological record sheds light on the 3D patterns of lithospheric deformation. Physical structure of the lithosphere can be determined with seismic surface waves. Using computational petrology and thermodynamic databases, we can invert surface-wave and other data for temperature and composition at depth, equilibrium lithospheric geotherms and lithospheric thickness. It is essential to use accurate surface-wave measurements and fit them closely, to impose constraints on the models from other available data and physical relationships, and to tune the inversions so as to resolve parameter trade-offs. With these developments, thermodynamic inversions yield increasingly accurate models of the lithospheric temperature, thickness and internal structure, with important inferences on its dynamics, evolution and controls on deformation and volcanism.

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The lithospheric structure of the Alpine-Pannonian-Carpathians-Dinarides system: Inferences from P and S receiver function analyses

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[7]MTA FI Lendület Pannon LitH2Oscope Research Group, Institute of Earth Physics and Space Science, Sopron, Hungary

We perform a comprehensive P-to-S and S-to-P receiver function analyses to determine the depth of lithospheric discontinuities in the Eastern Alps, Pannonian Basin, Carpathians, and the Dinarides. The Pannonian Basin of Central Europe hosts thick sedimentary deposits of up to 7 km thickness in extensional half-graben geometries overlying the crystalline orogenic basement. Prior to this study, the mapping of the seismic discontinuities in the lithosphere beneath the investigated area was not uniform and the estimated depth values bore non-negligible uncertainties.

Owing to the combined, dense station coverage of more than 380 seismological stations we can achieve hitherto unprecedented spatial resolution. Our study is based on two decades (2002–2022) of broadband waveforms with uniform automatic waveform processing and quality control procedures. This detailed procedure provides new geological and geophysical information about the lithosphere of the region.

The obtained results allow us to infer a 3D lithospheric structural model of the region. We have developed a new interpolation and visualization algorithm. We mapped the thickness of the main crustal layers and the lithosphere, together with an estimate of their uncertainties.

We present the sedimentary thickness map, the first Conrad depth map and an improved, detailed Moho map, the first upper and lower crustal thickness maps, as well as the lithospheric (Lithosphere-Asthenosphere-Boundary and Mid-Lithospheric-Discontinuity) thickness map obtained from receiver function analysis. We show migrated Common Conversion Point cross-sections beneath the Pannonian Basin and Carpathians, and the Eastern Alps–Pannonian Basin transition zone.

Finally, we compare and jointly interpret the results of the receiver functions with previous geophysical investigations and seismic tomography models.

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S17a - Structure and evolution of the lithosphere in the circum-Mediterranean

Identifying Seismic Anisotropy Patterns and Improving Tomographic Images in the Alps and Apennines Subduction Environments with Splitting Intensity

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Active and past subduction systems influence the interpretation and understanding of current tectonics and velocity structures of the upper mantle of the Alps and Apennines. Computational advances over the years made it possible to identify remnant and active slabs up to great depths. 824 stations were used in this study to calculate splitting intensities in an automated process. Compared to SKS measurements, more stable fast polarisation directions were recovered with a pattern paralleling the strike of the mountain belts and a clockwise rotation in the Alps. While strong anisotropy has been recovered over the bulge of the Alps and Apennines chain, weaker anisotropy has been found beneath the Po plain, the eastern sector of the Apennines, in the western sector of Sicily and the external European domain. On the other hand it is still difficult to get reliable depth-dependent anisotropy, therefore we adopted the tomographic method relying on the inversion of splitting intensity (SI). Since it is linearly related to the elastic perturbations of the medium through the 3-D sensitivity kernels, SI can be easily inverted, providing the basis for a better interpretation of shear wave splitting measurements. The anisotropic tomography models obtained so far allowed us to recover the most prominent splitting patterns and see some changes with depth, especially for the strength of anisotropy. Directional changes often seem to be related to the slab domain or dimension (e.g. Central Italy or Sicily).

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S17a - Structure and evolution of the lithosphere in the circum-Mediterranean

Moho depths for Italian region by the inversion of ground-based gravity data

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The complex geophysical structures in the Italian region make it even more difficult to invert gravimetric data for determining the depths of the Moho. However, a revised computation approach based on windowed Least Square Collocation has been set up to deal with local features like Ivrea Body, important sedimental basins, tectonics and orogenic activities. The Italian ground-based gravity dataset has been used to determine the Moho depths over land and sea areas and the gravimetric model have been compared with the Moho depth values obtained by different techniques as the seismic reflection and refraction profiles, receiver functions and seismic surface waves. Nowadays different solutions are available for some areas, as the Alpine Region, however the Moho depths can differ for several km, so the gravimetric Moho validation represents also a validation of the seismic models, because the gravimetric inversion represent an independent estimate with respect to the seismic solutions.

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S17a - Structure and evolution of the lithosphere in the circum-Mediterranean

Subducted european crust in the Eastern Alps: Evidence from teleseismic receiver functions

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The tectonic structure of the Eastern Alps is heavily debated with successive geophysical studies that are unable to resolve areas of ambiguity (e.g., the presence of a switch in subduction polarity and differing crustal models). In order to better understand this area, we produce a high resolution Moho map of the Eastern Alps based on a dense seismic broadband array deployment. Moho depths were derived from joint analysis of receiver function images of direct conversions and multiple reflections for both the SV (radial) and SH (transverse) components, which enables us to map overlapping and inclined discontinuities. We observe the European Moho to be underlying the Adriatic Moho from the west up to the eastern edge of the Tauern Window. East of the Tauern Window, a sharp transition from underthrusting European to a flat and thinned crust associated with Pannonian extension tectonics occurs, which is underthrust by both European crust in the north and by Adriatic crust in the south. The Adriatic lithosphere underthrusts northward below the Southern Alps and becomes steeper and deeper towards the Dinarides where it dips towards the north-east. Our results suggest that the steep high velocity region in the mantle below the Eastern Alps, observed in tomographic studies, is likely to be of European origin.

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S18a - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

On transient creep in Earth's upper mantle: How to link geophysical observations on short-term deformation to long-term geological deformation?

DOI: 10.57757/IUGG23-0352 - [LINK]

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Rheological properties of Earth can be inferred from several types of time-dependent deformation including the post-glacial isostatic adjustment (GIA) and post-seismic deformation (PSD). The time scale of deformation is ~10^3-10^4 y for GIA, and 1-10 y for PSD, as compared to 10^7-10^8 y for geological deformation. The stress magnitude associated with GIA and PSD is not much different from that with geological deformation, but the strain is vastly different: ~ elastic strain (or less) for GIA and PSD, while it is much larger than elastic strain for geological deformation.

In order to link rheological properties inferred from small strain phenomena to rheological behavior associated with large strain, we need to understand the physical mechanisms of transient creep. Currently two models are proposed: (i) intra-granular and (ii) inter-granular transient creep. In the former, transient creep behavior is attributed to dislocation dynamics within a grain (with a given slip system), while in the latter, it is attributed to grain-grain interaction involving multiple slip systems. We have conducted deformation experiments of olivine aggregates and single crystals together using a synchrotron facility to test these models. Strain is measured by X-ray imaging while stress is measured by radial X-ray diffraction form a polycrystalline olivine as well as a pyrope stress sensor. The results show that in a polycrystal, the average stress is near the lower end of stress levels inferred from various diffraction planes (hkl) at small strains, but it becomes close to the upper end at large strains (with a transition strain close to the elastic strain). This suggests a transition in the rate controlling slip systems with strain. In comparison, the transition strain for a single crystal (for the [001] slip) is substantially smaller than elastic strain. We conclude that in a deforming polycrystal olivine, single crystals attain steady-state quickly and the transient behavior is largely controlled by the evolution of controlling slip systems caused by grain-grain interactions. Because sensitivity of deformation on some parameters such as water content differs among different slip systems, applications of rheological properties inferred from short-term geophysical with long-term deformation needs to be made with a great care.

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Olivine radiative heat transport can cause premature dehydration of subducting slabs

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Temperature is a key parameter that governs the physical behavior of subducting slabs: their buoyancy, rheology, phase transitions, and dehydration reactions. Upon their descent into the mantle, subducting slabs are heated by diffusion, which is controlled by the total thermal conductivity. In mantle minerals, two microscopic mechanisms contribute to total conductivity: lattice and radiative heat transport. The crystal structure of a mineral determines its lattice conductivity, whereas the optical absorption coefficient determines the radiative component. Both depend on P, T, composition, and phase polymorphs. Nevertheless, in thermal evolution models of slabs, lattice component is often assumed constant while radiative is usually ignored, because its variation with P, T, phase, and composition is generally unconstrained. Here, we measured the optical absorption coefficient of olivine at T up to 1000 K and P up to 10 GPa to infer its radiative thermal conductivity. We found that radiative contribution is as important as lattice contribution for diffusing heat transport, representing 40-50% of olivine´s total conductivity. We further modelled slab thermal evolution with 2D finite-difference method. Accounting for radiative heat transport produces slabs that are ~200 K warmer than the models with only the lattice contribution. Our models show extensive dehydration of the upper 10 km of the slab at depths of ~140-280 km. The released water fails to reach the MTZ, and it might be responsible for the intermediate-deep seismicity. Water delivery into the MTZ is therefore only possible within the cold slab core (~30 km) or inside fast sinking slabs (>10 cm/year).

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Squirt-flow in the crust and seismic intrinsic Q: Some micro-physics for naturally fractured formations

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Dissipation of elastic energy by way of the "squirt-flow" mechanism is considered as a predominant cause of the frequency dependence of the quality factor Q observed in vibrated fluid-saturated rock samples. Models of the process (e.g. BISQ) have long been useful to infer key properties of fluid-saturated granular rocks but extension of such modelling to crustal-scale formations has yet to be thoroughly investigated. Central to the modelling is a micro-scale locus of dissipation represented by a dual pore system, with one part more compliant than the other – a system that is required to have characteristic dimensions. Rock formations in the brittle crust are highly fractured, with fracture-wall topography known to be fractal; thus, ab initio, the rough, porous interstitial space within natural fractures appears to have no "characteristic dimensions". However, as argued here, a closer look at such inter-space does reveal a characteristic dimension, one that is quantifiable by hydraulic properties of rock formations measured at the crustal scale. The structure of the permeable space in between two fractal fracture walls suggests that a locus of dissipation therein can be modelled as a fluid-saturated dual pore system, with a compliant narrow cylindrical gap centre, surrounded by a less compliant permeable ring. The complex stiffness of such a system under oscillatory forcing is solved for, subjected to boundary conditions imposed by the inter-space structure, and subsequently scaled-up to field-scale measurements. Results are presented in term of seismic Q versus frequency of forcing, under realistic thermodynamic conditions of a brittle crust.

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Evidence for amorphous calcium carbonate originated mid-lithospheric discontinuities

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Cratonic lithosphere is a vast host for deep recycled carbon, trapping up to several weight percent CO_2 among its compositions at depths overlapping the seismic mid-lithospheric discontinuities (MLDs). However, the role of carbonates, especially for the latest discovered amorphous calcium carbonate ($CaCO_3$), is underestimated in forming MLDs. Using the pulse-echo-overlap method in a Paris-Edinburgh press coupled with X-ray diffraction, we explored the acoustic velocities of $CaCO_3$ under high pressure-temperature (*P*-*T*) conditions relevant to the cratonic lithosphere. Two anomalous velocity drops were observed associated with the phase transition from aragonite to amorphous phase as well as with pressure-induced velocity drop in amorphous phase around 3 GPa, respectively. Both drops are comparable with approximately 35% and 52% reductions for compressional (V_P) and shear (V_S) wave velocities, respectively. The V_P and V_S values of the amorphous $CaCO_3$ above 3 GPa are about 1/2 and 1/3 of those of the major upper-mantle minerals, respectively, and they are the same with aragonite below 3 GPa. These velocity reductions by the presence of $CaCO_3$ would readily cause MLDs at depths of 70–120 km dependent on the geotherm even if only 1-2 vol.% $CaCO_3$ presents in the cratonic lithosphere. The $CaCO_3$-originated MLDs is weak so as to be expected to influence the stability, rifting, and delamination of the craton.

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Geophysical Signatures of Critical Minerals in Felsic Igneous Provinces Along a Tectonic Rift Shoulder in West Texas

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Identifying available and minable critical minerals worldwide is crucial to stabilizing the supply chains and the markets for these minerals. Because of the low concentrations of critical minerals throughout the world, we focus on identifying geophysical signatures from geological structures associated with the origin and geochemical character of these minerals. In this work, we identify geophysical signatures generated by critical minerals in west Texas using publicly available geophysical datasets, including aero-radiometric, topographic, aero-magnetic, and gravity datasets, on both local and regional scales. We also compile geological information along with the geophysical datasets in caldera systems at various evolution stages, specifically studying the subsurface structures of felsic igneous provinces along a tectonic rift shoulder in west Texas, including what we believe are undeveloped calderas in a well-studied area consisting of laccoliths. We are creating a geological geochemical and geophysical signature database of potential critical mineral sites in west Texas because rift shoulders have an unusual concentration of critical minerals. These databases are cross referenced with other regions that show similar characteristics. For example , Round Mountain is a site currently under development for HRREs and other critical minerals. However, some sites may be economically feasible for exploration of critical minerals, but may never be exploited because they lie in protected regions.

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S18b - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

Seismic thermography

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Seismic tomography maps seismic-velocity distributions within the Earth. Lateral variations of seismic velocities in the mantle depend primarily on variations in temperature. Thus, tomography gives us a proxy for the thermal heterogeneity in the Earth, of great interest because it determines the thickness and mechanical strength of the lithosphere and the density variations and convection patterns in the sub-lithospheric mantle. Obtaining accurate, quantitative mapping of temperature, however, is not straightforward. Tomographic models are non-unique solutions of inverse problems, regularized to yield solutions with properties such as smoothness or small model norm, not physical plausibility. For example, lithospheric geotherms computed from tomographic models typically display unrealistic temperature oscillations, with implausible temperature decreases with depth. If a tomographic model is all we have, a reasonable approach is to look for a physically plausible geotherm that fits seismic velocities in the entire lithospheric depth range best, in some sense. A generally more accurate approach is to invert seismic data, from the start, directly for what we want to know. Using computational petrology and thermodynamic databases, we can invert seismic-surface-wave and other data for temperature and composition at depth, equilibrium lithospheric geotherms and the lithospheric thickness. We must use accurate surface-wave measurements and fit them closely; impose constraints on the models from other available data and physical relationships; and tune the inversions so as to resolve essential parameter trade-offs. With these developments, thermodynamic inversions yield increasingly accurate models of the lithosphere's temperature, thickness and internal structure, with important inferences on its dynamics and evolution.

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A new global crust model: ECM22

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Despite 160 years of probing the world crust, due to lack of seismic and ground gravity observations, there are still white spots in the worlds' crustal thickness map. The crustal structure in those regions is among the least understood of the Earth's continental areas, and variations in basic but fundamental parameters - such as crustal thickness - are still poorly constrained over large areas. Recent research has shown that satellite gravity-based crustal modeling in regions with limited seismological coverage can provide unique insights in crustal thickness and underlying geodynamical processes.

In almost all of these cases the gravity signal related to crustal structure is isolated by applying 3 different corrections: topography, sediments, and upper mantle structure.

Of these three, the upper mantle correction is least well addressed. It doesn’t account for any lateral inhomogeneity upper mantle composition close to the crust-mantle boundary. As a result, satellite gravity data reductions for upper mantle structure are a source of uncertainty.

Our new model includes a new state-of-the-art upper mantle correction. By combining satellite gravity and seismic tomography, we have formulated a new methodology to integrate potential field data inversions, tomographic modelling, and petrolophysics into a single inversion scheme. Our crustal thickness model ECM22 has therefore more accurate crustal thickness values, is seismically fitting better than previous models, and is now also consistent with gravity observations: up to a factor 85 times more accurate than e.g. CRUST1.0 and 4 times better than the GEMMA crustal model.

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S18b - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

Thermal and compositional state of the South Africa cratonic region from seismic and gravity models

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Earlier studies revealed the effect of different degrees of depletion on lateral/vertical velocity and density variations in the upper mantle of the Precambrian cratons. The South Africa cratonic region includes the Kaapvaal and Zimbabwe craton, whose deep and fast lithospheric roots are likely depleted in heavy constituents. In contrast, there exist regions, such as the Limpopo belt and Bushveld Complex, which are characterized by negative velocity anomalies in the upper mantle, likely indicating a more fertile composition. To unravel the origin of these anomalies and link them to the tectonic history of the area, we apply an integrative technique based on a joint interpretation of the seismic tomography and gravity data, which can discern temperature and compositional variations. For this purpose, we combine the global surface seismic tomography model [1] with the embedded regional model [2], derived from teleseismic tomographic inversion of the S-body wave dataset recorded by the Southern African Seismic Experiment. The combined seismic model is inverted for temperature, assuming an initial fertile composition based on the xenolith data [3], using a mineral physics approach [4]. The composition and temperature of the upper mantle are iteratively changed to fit the residual density, obtained from the joint inversion of the residual gravity and residual topography. The key results show different structures and properties of the upper mantle, improving our understanding of the South African cratonic lithosphere.

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[2] Youssof et al., 2015. http://dx.doi.org/10.1016/j.epsl.2015.01.034

[3] Griffin et al., 2004. doi:10.1016/j.chemgeo.2004.04.007

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Earlier studies revealed the effect of different degrees of depletion on lateral/vertical velocity and density variations in the upper mantle of the Precambrian cratons. The South Africa cratonic region includes the Kaapvaal and Zimbabwe craton, whose deep and fast lithospheric roots are likely depleted in heavy constituents. In contrast, there exist regions, such as the Limpopo belt and Bushveld Complex, which are characterized by negative velocity anomalies in the upper mantle, likely indicating a more fertile composition. To unravel the origin of these

anomalies and link them to the tectonic history of the area, we apply an integrative technique based on a joint interpretation of the seismic tomography and gravity data, which can discern temperature and compositional variations. For this purpose, we combine the global surface seismic tomography model [1] with the embedded regional model [2], derived from teleseismic tomographic inversion of the S-body wave dataset recorded by the Southern African Seismic Experiment. The combined seismic model is inverted for temperature, assuming an initial fertile composition based on the xenolith data [3], using a mineral physics approach [4]. The composition and temperature of the upper mantle are iteratively changed to fit the residual density, obtained from the joint inversion of the residual gravity and residual topography. The key results show different structures and properties of the upper mantle, improving our understanding of the South African cratonic lithosphere.

References

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S18b - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

The influence of Moho depth on the seismic / density structure of the Antarctic upper mantle

DOI: 10.57757/IUGG23-1697 - LINK

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With its hostile and remote environment, information on Antarctica's geologic history and its internal geophysical structure remains today the most incomplete on Earth. In particular, Moho depth estimate studies are in disagreement by more than 10 km in several regions and, the Antarctic upper mantle remains among the most poorly imaged regions in the Earth.

In this study, we explore the impact of using different Moho surfaces on the reconstruction of the 3D density and velocity parameters beneath the Antarctic continent.

To achieve this goal we selected as input for the used optimization algorithm (Sequential Integrated Inversion, Tondi et al., 2012) four Moho depth estimates, which we believe to be the most representative of the last studies on the continent: (a) a pure gravimetric Moho (Borghi, 2022); (b) a depth to Moho (Baranov et al., 2018) recovered using the BEDMAP2 subglacial relief (Fretwell et al., 2013) together with results from the analysis of recent seismic data (Baranov and Morelli, 2013; Chaput et al., 2014) and gravity constraints; (c) a seismological Moho (An et al., 2015); (d) a Moho depth estimate constrained by both satellite gravity and seismological information (Pappa et al., 2019).

To complete the starting information, we exploited: (1) the surface wave tomography of the Antarctic upper mantle (Danesi and Morelli, 2001) and (2) the gravity database synthetized by the global satellite gravity model GO_CONS_GCF_2_TIM_R6e (Zingerle et al., 2019).

Results show the crucial implications of the Moho topography on the recovered geophysical parameters, especially in little explored areas.

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S19a - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

A new probe for geofluids? Measurements of attenuation anisotropy using instantaneous frequency

DOI: 10.57757/IUGG23-4062 - LINK

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The presence of fluids in closely aligned fractures is important for a range of processes within the Earth. In the near-surface, understanding systems of fluid-filled fractures is important in various applications such as geothermal energy production, monitoring CO_2 storage sites and exploring for metalliferous sub-volcanic brines (e.g., Blundy et al., 2021). In the mantle, melting is an important geodynamic process, exerting control over mantle composition and dynamic processes. Upper mantle melting weakens the lithosphere, facilitating rifting (Kendall et al., 2005) and other surface expressions of tectonic processes.

Models of aligned fluid-filled fractures, or inclusions with small aspect ratios, predict both velocity and attenuation anisotropy for shear-waves (e.g., Hudson, 1982; Chapman 2003). Forward modelling shows that attenuation anisotropy is highly sensitive to important fracture properties, such as fracture length and orientation, and can be frequency dependent. Attenuation anisotropy can be observed by measuring shear-wave splitting as the two separated shear-waves experience a different seismic quality factor as they propagate through the anisotropic medium.

Measurements of attenuation anisotropy therefore offer a new approach to seismically detect fluids in the subsurface. Here we present a method for measuring attenuation anisotropy using an adaptation of the instantaneous frequency method of Mathenay and Nowack (1995). We explore the potential of this technique using synthetics and make measurements of attenuation anisotropy in SKS data collected at the Yellowknife array, Canada, and at stations across the Main Ethiopia Rift. These results highlight the potential for attenuation anisotropy as a tool to detect geofluids in the subsurface.

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Ambient noise tomography reveals the affinity of the Tan-Lu Fault to regional deformation in Eastern China

DOI: 10.57757/IUGG23-0368 - LINK

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In Eastern China, complex tectonic structures of high geological/geophysical relevance suggest multiple subductions in the region making the region an ideal physical laboratory for investigating the feedback effect of subduction on the continent. In particular, subduction could have resulted in the formation of the Tan-Lu Fault Zone (TLFZ); a tectonic structure believed to have significantly aided the instability of the lithosphere and as well, played an essential role in the further modification of the lithosphere. To provide additional observational constraints on the fault activities such as its affinity to regional deformation, we took advantage of the ambient noise dataset to produce joint tomography models of Vsv (isotropic and azimuthal anisotropy) across the TLFZ. First, the models reveal structural segmentation, with structures that trend in the direction of the strike of the TLFZ. The isotropic Vsv shows a widespread low velocity in the lower crust, which could serve as a stress accumulator for the reactivation of faults. The polarization of azimuthal anisotropy in the TLFZ and the Zhangbaling uplift are NNE-SSW to N-S; sub-parallel to the strike of the fault in the crust and uppermost mantle. The trend of the anisotropy mimics the shape of the TLFZ in the crust and the uppermost mantle, which confirms that the Tan-Lu fault is a deep-seated lithospheric structure. This may also suggest that the fault controls the anisotropy and hence, the deformation in the region. These models highlight the dominant control of the fault on the regional deformation and geodynamic processes in eastern China.

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S19a - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Shear-velocity anisotropy in the lower crust of the Bohemian Massif from ambient noise tomography

DOI: 10.57757/IUGG23-1686 - LINK

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Previous research of the Bohemian Massif (BM) crust using ambient noise tomography (ANT) indicates a transversely isotropic layer in the lower crust (Kvapil et al., 2021). In this study, we have developed a new method for extracting seismic anisotropy from dispersion curve measurements in the regional scale using synthetic ray-path modelling over reference isotropic 3D v_{SV} model. We examine how the derived seismic anisotropy correlates with the major tectonic units of the BM.

Seismic anisotropy records the stress/strain conditions of each originally independent tectonic microplate during the formation of the BM crust. We use ambient noise cross-correlation data from the seismic stations included in the AlpArray passive seismic experiment with its complementary PACASE experiment and data from PASSEQ experiment which complement the sparse coverage in the northern part of the BM. Our anisotropic inversion procedure is proving to be an efficient tool for measuring seismic anisotropy in the lower crust on a dense grid directly from Rayleigh and Love wave dispersion curves.

We calculate synthetic Love velocities (v_{SH}) from the 3D isotropic v_{SV} model and compare the synthetic v_{SH}/v_{SV} with measured v_{SH}/v_{SV}. The higher ratio of measured v_{SH}/v_{SV} to synthetic v_{SH}/v_{SV} proves the existence of velocity anisotropy in the lower crust of the BM in the reference ANT model (Kvapil et al., 2021). We show that variations in azimuthal anisotropy are period dependent, with zonation of fast velocity directions on a regional scale; this can provide constraints for the reconstruction of geodynamic processes during the formation of the BM.

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S19a - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Understanding sub-lithospheric upper mantle anisotropy beneath the oceans with seismology and geodynamics

DOI: 10.57757/IUGG23-1763 - LINK

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While the presence of anisotropy in the uppermost mantle is well established, its detailed patterns are still debated. We present SPacific-rani, a new upper mantle radially anisotropic model of the Pacific which builds on the global whole mantle radially anisotropic model SGLOBE-rani by including additional data along with improved waveform modelling based on the spectral element method. SPacific-rani shows an asymmetry at the East Pacific Rise, requiring stronger radial anisotropy to the West of the East Pacific Rise than to the East, which is possibly due to lattice preferred orientation produced by shear-driven asthenospheric flow beneath the South Pacific superswell. Moreover, SPacific-rani shows a reduction in radial anisotropy with lithospheric age, possibly due to a deviation from horizontal flow as the mantle is entrained with slabs. In order to interpret existing models of upper mantle anisotropy beneath the oceans we develop 2D ridge flow models combined with mantle fabric calculations. We find that faster plates generate higher tectonics stresses and strain rates which lower the dislocation creep viscosity and lead to deeper anisotropy than beneath slower plates. By applying a tomographic filter to the geodynamical models, we retrieve a flat depth-age trend and stronger anisotropy beneath faster plates, which correlates well with existing 3D global anisotropic mantle models. Our predictions and observations suggest that as plate speed increases from 2 to 8 cm/yr, radial anisotropy increases by ~0.01–0.025 in the upper 100–200 km of the mantle between 10 and 60 Ma.

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S19a - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Seismic anisotropy and upper mantle flow in southeastern Mexico inferred from teleseismic and local intraslab earthquakes

DOI: 10.57757/IUGG23-2122 - LINK

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Silver and Chan (1991) covariance method was used to measure shear-wave splitting for both teleseismic and local intraslab earthquakes. Teleseismic measurements are consistent with subslab entrained flow below the subducted Cocos slab and with corner flow in the mantle wedge except in Chiapas where the fast polarization directions show greater variability and short delay times. Local measurements can be divided into three regions: The first region is located southeast of the Tehuantepec ridge extension. The measured fast polarization directions show a trench-parallel orientation that can be interpreted to result from the presence of a serpentinized mantle wedge beneath the forearc and a trench-parallel flow through the mantle wedge core. The second region is located northwest of the Tehuantepec ridge extension. Northeast of the 100 km isodepth contour of the Cocos slab the fast axes are trench perpendicular. This could be explained assuming the development of A-type olivine fabric and the existence of corner flow driven by the downdip motion of the Cocos slab. Between the 60 and 100 km isodepth contours, measurements are consistent with the presence of a serpentinized mantle wedge. Right above the Tehuantepec ridge extension, a change in the fast polarization directions from trench-normal to trench-parallel could suggest a change in the mantle flow pattern and could be evidence of a vertical tear in the Cocos slab coincident with the Tehuantepec ridge extension. Lastly, the third region is located above the subhorizontal Cocos slab where crustal faults seem to be the dominant factor producing the observed anisotropy.

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S19b - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Lithospheric fabric and active mantle flow beneath Canada: Evidence from depth-dependent seismic anisotropy

DOI: 10.57757/IUGG23-2092 - LINK

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Canada presents an excellent opportunity to study lithospheric and sublithospheric processes due to its preservation of ~4 billion years of geological history. Deformation from past tectonic processes is preserved in the thick lithosphere of the Canadian Shield, in contrast to the active tectonics and thin lithosphere in the Canadian Cordillera. Such large variations in lithospheric thickness, whether on a sharp or gradual lateral scale, likely perturb mantle convective flow beneath the continent, adding complexity to sublithospheric fabric.

We use dispersion data from teleseismic Rayleigh waves to investigate upper-mantle structure beneath Canada and the central-northern USA. For periods of 20 to 220 seconds, azimuthal coverage of inter-station paths is sufficient to resolve isotropic heterogeneities and azimuthal anisotropy across the study area. Significant lateral variation in azimuthal anisotropic parameters and changes as a function of period suggest complex lithospheric and sublithospheric fabric. However, the stratification of the anisotropy is difficult to interpret directly from the phase velocity maps due to the wide depth range sampled by each period.

To investigate the depth-dependence of azimuthal anisotropy, we extract the 1D dispersion parameters at selected points in the phase velocity maps. An anisotropic depth inversion is carried out to investigate the relative roles of 'frozen' lithospheric fabric and lattice-preferred orientation related to active mantle convective flow. We also search for stratification in azimuthal anisotropy with depth within the thick lithosphere of the Canadian Shield and speculate on the tectonic processes that contribute to such layering.

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S19b - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Variation of seismic anisotropy with depth in deformational regimes of continental plates

DOI: 10.57757/IUGG23-3661 - LINK

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The correlation between mantle flow and seismic anisotropy emphasizes its key role in understanding tectonic processes. While global geodynamic modelling of asthenospheric mantle flow results in a good correlation, the large spatial variation of seismic anisotropy beneath continents indicates a considerable complex contribution of the shallow lithosphere, which is not yet well understood. A detailed imaging of anisotropy with depth is therefore an important challenge for seismic investigation.

Here, we present our current advances in improving the depth resolution based on receiver function and SKS-splitting techniques applied at the continental margins of the European Alps and Central Appalachians.

Classical shear-wave splitting techniques are mostly used to infer a single anisotropic layer. This becomes misleading for continental margins with complex deformation. An azimuthal variation of splitting parameters is an indication for vertical layering of anisotropy and can be analyzed systematically providing insight into these complexities. However, this approach allows no direct constraint on the depth distribution. Recent developments involve the calculation of sensitivity kernels for Splitting Intensity observations, which allows us to consider the laterally broadened sensitivity for the anisotropic structure with depth. A requirement of this tomographic technique is a dense station spacing, which is satisfied by a growing number of seismic deployments.

The increased lateral stress in deformational regimes at shallow levels results in a possible contamination of shear-wave splitting by crustal anisotropy. We suggest a stepwise approach in which receiver functions are examined for their harmonic variation with backazimuth to determine and correct for significant anisotropic crustal effects.

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S19b - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

3D self-consistent anisotropic models of the lithosphere along the Bohemian Massif-Eastern Alps north-south transect (central Europe)

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Body-wave recordings from passive seismic experiments AlpArray-EASI (2014-2015) and AlpArray Seismic Network (2016-2019) are evaluated to image the upper mantle large-scale anisotropy and to model the lithosphere-asthenosphere boundary (LAB) beneath the western part of the Bohemian Massif and the Eastern Alps. We analyze P-wave traveltime deviations and interpret them along with results of splitting parameters from core-mantle refracted shear waves at 240 broad-band stations in about 200 km broad and 540 km long band along 13.3° E longitude. The body-wave anisotropic parameters are inverted jointly for 3D self-consistent anisotropic-velocity models of individual mantle lithosphere domains, assuming hexagonal symmetry with inclined ‘slow’ or ‘fast’ axes. To control the depth extent of the fabric, we apply coupled 3D anisotropic-isotropic P-wave tomography (Munzarova et al., 2018). Anisotropic signals in body waves are consistent within sub-regions and often sharply change at tectonic boundaries. The coincidence of boundaries of the anisotropic models of the mantle lithosphere domains with main tectonic features, correlation of the anisotropy depth extent with the LAB models as well as a decrease of anisotropy strength in the sub-lithospheric mantle support fossil origin of the directionally varying component of detected anisotropic fabrics of the continental mantle lithosphere.

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S19b - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Lithospheric architecture and deformational patterns below the Eastern Ghats Mobile Belt: an integrated seismological perspective

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Understanding of the evolutionary geodynamics of the Eastern Ghats Mobile Belt (EGMB), is crucial to reconstruction of the Rodinia and Gondwana supercontinents. However limited aspects of its structure and evolutional origin are known. Based on lithological assemblage and geochronological data, EGMB is divided into multiple heterogeneously deformed terranes. Recent seismological studies across the EGMB-Archaean craton boundary adds new perspective regarding the deformation of the region and its correlation with East-Antarctica. Integrated studies reveal heterogeneous structure across the craton and mobile-belt characterised by 32-37km, ~42km and 110-160km, 80-120km thick crust and lithosphere respectively, suggesting collisional thrusting of EGMB against the Archean Cratons that explains the abrupt changes in crustal thickness across the craton-mobile belt. The influence of mantle-plumes, owing to the trajectory of the Indian subcontinent across the Kerguelen/Crozet hotspots, results in thinner cratonic-lithosphere than its erstwhile neighbours in the Gondwanan configuration. Observations indicate crustal amalgamation of different blocks in the evolution of the present EGMB, akin to observations from East-Antarctica also touted to be composed of different Proterozoic crustal terranes. Parity in crustal thickness is also noted. Strained minerals along the upper-mantle fabrics influence the variation of anisotropic parameters across different domains, indicating large-scale pervasive deformation related to various collisional-rifting episodes. The most notable being the disparity in anisotropic trends and lithospheric architecture across the eastern and western Phulbani Domain establishing them as separate blocks. Thereby, deeper understanding into the complex geodynamics of EGMB and its correlation with East-Antarctica can be achieved through unified geophysical studies across both the regions.

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S19b - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Seismic anisotropy beneath a transect of Kumaon Himalaya using shear wave splitting analysis

DOI: 10.57757/IUGG23-2017 - LINK

Sivaram Krishnavajjhala[1], *Sandeep Gupta*[1], *Sudesh Kumar*[1], *Prasad Bnv*[1], *Dixith M Sai*[1], *Saneesh Ali*[1], *Vishal Rawat*[1]
[1]*CSIR- National Geophysical Research Institute, Seismological Imaging Group, Hyderabad, India*

We explore the pattern of seismic anisotropy beneath a ~300 km transect in the Kumaon Himalaya, an active, orogenic region formed by the collision between the India-Eurasian plates, and carrying world-wide attention for its mysterious geometry and seismic potential. Applying the shear wave splitting analysis of the teleseismic core-refracted phases (SKS, SKKS, PKS and PKKS) on a linear profile of 32 broadband seismograph stations, we uncover the signatures of enigmatic strain histories and mantle dynamics. The measured shear wave splitting parameters i.e. Φ (Fast Polarisation Direction, FPD) and δt (Delay Time, DT) carry extraordinary information of the anisotropy formed through the complex mantle-deformation. We observe a strong dependence of the splitting data on the back-azimuth directions, which fits fairly well with a two-layer anisotropy model, with the lower layer having a low dipping angle at most of the stations. We present a geodynamic model depicting the preserved and the current situation of the compression-forces at the India-Asia collision zone. Incidentally, the mean Φ are primarily sub-parallel to the North East (NE)-oriented absolute plate motions (APM), and nearly orthogonal to the major geological boundaries in the Higher Himalaya. In the Lesser Himalaya, the mean Φ are nearly orthogonal to the APM and are sub-parallel to the surface expressions of major geological features. Similarly, we observe a wide variation in the mean δt. Our detailed analysis indicates a predominantly asthenospheric source of anisotropy, and a possible slab-tearing for this segment of the Kumaun Himalaya.

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δt. Our detailed analysis indicates a predominantly asthenospheric source of anisotropy, and a possible slab-tearing for this segment of the Kumaun Himalaya.

S20a - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

Outreach and engagement to ensure the success of an Earthquake Early Warning System for Canada

DOI: 10.57757/IUGG23-5027 - LINK

Alison L. Bird[1], Henry C.J. Seyward[1], Stephen Crane[1], Nicholas Ackerley[1]
[1]Canadian Hazards Information Service, Natural Resources Canada, Ottawa, Canada

Natural Resources Canada (NRCan) is developing a national Earthquake Early Warning (EEW) system for Canada. The network will focus on regions with a) an expectation of strong earthquakes, and b) concentrations of population and/or critical infrastructure (CI). These regions include parts of British Columbia, Ontario and Quebec.

The system will facilitate mitigation of earthquake impacts, allowing for timely and appropriate response actions by the public, emergency measures organizations, CI operators, and other industrial facilities. However, for the system to be effective, a culture of awareness is necessary to ensure appropriate protective actions are taken when alerts are received.

A coordinated public education campaign is underway to help achieve this. NRCan is hosting workshops and other outreach activities with CI operators to ensure they are aware of the benefits of installing systems that automatically translate EEW alerts into protective actions. Simultaneously, NRCan is encouraging equipment providers in Canada to develop such automated systems. In these efforts, NRCan is collaborating with federal and provincial public safety organizations, private and international partners, and Non-Governmental Organizations. This will ensure that EEW messaging is authoritative, consistent and accessible. Social science research by collaborators is underway and will guide the education of vulnerable populations including First Nations peoples, new immigrants, people with low income, and the elderly.

By making it possible to take safe actions before the arrival of potentially harmful shaking, the national EEW system will contribute to the reduction of earthquake risk in Canada.

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S20a - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

A historical case study teaching about earthquake intensity and magnitude: Research to help Canadians better understand earthquake early warning alerts

DOI: 10.57757/IUGG23-4695 - LINK

Esther Muturi[1], *Glenn Dolphin*[1]
[1]*University of Calgary, Department of Geoscience, Calgary, Canada*

Canada is developing an earthquake early warning system (EEWS) for implementation in 2024. To help prepare the Canadian public to take appropriate protective action when getting an EEW alert, educating them about the phenomenon of earthquakes is essential. To this end, we are developing a historical case study focusing on the conceptual development of earthquake intensity and magnitude. Historical case studies in science education have usually focused on helping learners understand the nature of science better, but they have also been effective in teaching scientific content.

The case study begins with the human experiences of earthquakes and how they used myths to explain the observations. The story then picks up in the 18th century and documents many different earthquakes (Lisbon, Portugal, 1755; Naples, Italy, 1857; Mino-Owari, Japan, 1891; Assam, India, 1897; San Francisco, USA, 1906; and Alaska, USA, 1964) and the development of understandings of what earthquakes are, how they happen, and how the concepts of intensity and magnitude played a role in those understandings.

The case study reveals the switch from mythic explanations to reasoned ones; that earthquakes are natural occurrences and therefore steps can be taken to mitigate death and destruction. The narrative distinguishes between an observational era and one of the instruments. After the development of the seismometer, there was a much more quantitative approach to seismology. A stark contrast between earthquake intensity (very concrete, yet subjective) and magnitude (abstract, yet calculated) became quite apparent. By focusing on this contrast, readers will develop a robust understanding of both conceptions.

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S20a - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

A three-pronged approach for understanding earthquake intensity and magnitude for increasing the efficacy of earthquake early warning alerts

DOI: 10.57757/IUGG23-4628 - LINK

Glenn Dolphin[1]
[1]*University of Calgary, Department of Geoscience, Calgary, Canada*

Geologic hazards put the lives and property of humans at risk. To mitigate such risks, countries have developed and implemented alerting systems that can warn people to take timely protective actions. Canada's geological context creates a risk of large earthquakes along its western provinces due to Cascadia subduction, and along the northern and eastern territories and provinces, mainly due to glacial rebound. In response to this risk, Canada is developing an earthquake early warning system (EEWS). Using the same foundation as the USGS's ShakeAlert. Canada's EEWS calculates the magnitude (energy released) and intensity (amount of shaking) of each event recorded. An alert gets sent once pre-determined thresholds for magnitude and intensity are met. Having the public take protective actions (such as drop, cover, and hold on) once they receive an alert is imperative to the success of the system.

The heart of our research is how the public understands earthquake intensity and magnitude. We investigate this focus from three directions:

- Historical–Documenting the conceptual development of earthquake intensity and magnitude, then creating a historical narrative to teach these concepts.
- Linguistics–The language used when talking about earthquakes, earthquake intensity, and magnitude, by the public on news and social media platforms.
- Socio-cultural–The state of seismicity education in Canada, how that education has developed through time, and how it compares to the contexts of other seismically active regions around the world.

This presentation builds an argument for the three approaches and delineates the products they will yield.

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S20a - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

Using Did You Feel It? data to trace people's understandings of earthquake magnitude and intensity

DOI: 10.57757/IUGG23-4546 - LINK

Jason Curtis Droboth[1]
[1]*University of Calgary, Department of Geoscience, Calgary, Canada*

The effective initial public adoption and proper sustained use of Earthquake Early Warning (EEW) systems depend, in part, upon effective education, outreach, and communication (EOC) campaigns. The success of such campaigns are themselves dependent upon strategic plans designed around audience needs, interests, codes, and understandings. From this, clear, concise, and easily comprehensible messaging and interactions should be implemented and repeatedly distributed through multiple trusted channels and sources.

While much work has been done on public perceptions of earthquake risks, little seems to have been done to explore how the general public understands and describes earthquakes, including their lived experiences with them, especially in terms of earthquake magnitude and intensity. Developing effective EOC strategies and messaging requires accurate knowledge of audiences' understandings of earthquake magnitude and intensity and the linguistic codes they use to describe them.

This presentation will share some preliminary results of a study looking at people's linguistic descriptions of their first-hand experiences of earthquakes by conducting qualitative analyses of thousands of public submissions to the USGS's *Did You Feel It?* survey concerning the 2019 California Ridgecrest earthquakes.

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S20a - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

Geographic information system (GIS) mapping evacuation routes and disaster education based on Android (application information systems) to raise public awareness

DOI: 10.57757/IUGG23-3179 - LINK

Rika Reviza Rachmawati[1]
[1]*National research and Innovation agency,*
Research Centre for Behavioural Economics and Circular, JAKARTA TIMUR, Indonesia

Indonesia is a country that crosses the Ring of Fire or active mountain paths. The region is 40,000 km in size and shaped like a horseshoe. Moreover, the plate-meeting path contributes to Indonesia's high earthquake risk. According to the Meteorological Climatology and Geophysics Agency (BMKG), Indonesia is a meeting point for three tectonic plates: the Indo-Australian plate, the Eurasian plate, and the Pacific plate. This causes many earthquakes, tsunamis, and volcanic eruptions that often occur in Indonesia. A natural catastrophe is an extreme occurrence that causes casualties, environmental damage, property loss, and psychological effects. With the availability of a Geographical Information System (GIS), information such as tsunami or earthquake evacuation routes and disaster education may be transmitted visually. The government has created several android applications. The application contains information about earthquakes, climate maps, flash floods, volcanic eruptions, landslides, and tsunami waves. Info BMKG, inaRISK Personal, My Earthquake Alert, Newest Earthquake Info, BMKG Real-time Earthquakes, WRS-BMKG, and MAGMA Indonesia are some of the applications available. Because the public may be alerted of the probability of a disaster in advance, this application can assist in reducing casualties in the case of a disaster. Once this application is operational, it is intended to assist relevant organizations in disseminating community-required information more promptly, precisely, and properly.

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S20a - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

Tsunami mitigation strategy through tsunami community preparedness training course

DOI: 10.57757/IUGG23-1335 - LINK

Madona Madona[1], *Nelly Florida Riama*[1]
[1]*Meteorological- Climatological and Geophysics Agency,*
The Education and Training Center, Jakarta, Indonesia

An advanced tsunami early warning system will not be sufficient for safe life if communities, especially in high-hazard risk areas, do not have adequate knowledge and capacity to respond to the early warning as well as to react and take action without official warning or guidance. The IOC Assembly declared the IOC Ocean Decade Tsunami Programme (2021-2030). This programme is dedicated to a safe ocean where life and livelihood are protected from tsunamis hazards. It is expected to establish 100% of communities at risk of tsunami prepared for and resilient to tsunamis by 2030 through the implementation of the UNESCO/IOC Tsunami Ready Recognition Programme and other initiatives. This could be achieved through a collaborative effort to meet a standard level of tsunami preparedness through the fulfillment of a set of established indicators. Therefore, BMKG in collaboration with Ocean Teacher Global Academy (OTGA) conducted Tsunami Community Preparedness Training in 2022. Tsunami Community Preparedness Training Course is a continuation of the previous training, namely the Tsunami Ready Training Course. Conducting this training is an effort of tsunami mitigation strategy from a capacity-building perspective. That training was addressed for local/national disaster management institution officers, government/ non-government organizations working in the disaster management field, and researchers of tsunami science. Moreover, we invite volunteers as an activator of an independent tsunami-ready community. Training is an effective attempt to enhance knowledge regarding how to build a resilient community, so we comprehensively evaluate its implementation until several months after the training has been completed.

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S01 - Posters - Observational Seismology - Open Session

Investigation of crust and lithosphere transition between the Alborz and the South Caspian basin in NW Iran

DOI: 10.57757/IUGG23-1598 - LINK

Shiva Arvin[1], *Farhad Sobouti*[1]
[1]*Institute for Advanced Studies in Basic Sciences IASBS, Earth Sciences, Zanjan, Iran Islamic Republic of*

We analyzed P and S receiver functions to investigate the structure of the crust and uppermost mantle beneath 37 temporary and 7 permanent broadband seismic stations located in the western Alborz region and coastline of the South Caspian Basin. We identified the geometry and depth of the Moho and the lithosphere-asthenosphere boundary under two different seismic profiles in the area. There is no evidence of underthrusting the South Caspian Basin beneath Alborz in our results. We believe that the oceanic or oceanic-like nature of the crust of the South Caspian Basin is unacceptable because of its 25-30 km crustal thickness, so we introduced the nature of the south Caspian basin as a continental crust with a sediment thickness of 20 km. We found evidence of underthrusting the Central Iran crust beneath the Alborz, and also the depth of Central Iranian moho in the northern flank of western Alborz goes to 68 km, which could be a sign of the presence of Paleottech sutures in this region. We also detect some evidence to identify the lateral displacements caused by the Lahijan fault zone. The presence of a discontinuity at depths of 120 to 140 km in S receiver functions results was considered evidence for the confirmation of the existence of lithosphere delamination under the western Alborz. Given the geometry seen from this discontinuity along the two different profiles, which are approximately perpendicular, we assume that the possible delamination is in its early stages

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S01 - Posters - Observational Seismology - Open Session

Seismicity and Tectonics of the Caucasus Region Revisited

DOI: 10.57757/IUGG23-1649 - LINK

István Bondár[1], *Tea Godoladze*[2], *Eric Cowgill*[3], *Gurban Yetirmishli*[4], *Stephen Myers*[5], *Tuna Onur*[6], *Irakli Gunia*[2], *Albert Buzaladze*[2], *Rengin Gök*[7], *Andrea Chiang*[5]
[1]*Research Centre for Astronomy and Earth Sciences- ELKH, Institute for Geological and Geochemical Research, Budapest, Hungary*
[2]*Ilia State University, x, Tbilisi, Georgia*
[3]*University of California, Earth & Planetary Sciences, Davis, USA*
[4]*Republic Seismic Survey Center of ANAS, x, Baku, Azerbaijan*
[5]*Lawrence Livermore National Laboratory, x, Livermore, USA*
[6]*Onur Seemann Consulting- Inc., x, Victoria, Canada*
[7]*National Nuclear Security Administration, x, Washington DC, USA*

Despite its role in Arabia-Eurasia convergence between the Black and Caspian Seas, the Caucasus region lacks a comprehensive catalog. To address the issue, the Lawrence Livermore National Laboratory and the Institute of Earth Sciences (IES) at Ilia State University generated a new, comprehensive seismic catalog for the Caucasus region by combining data in the IES bulletin with bulletins of the Republic Seismic Survey Center of Azerbaijan, monitoring centers in Turkey and Armenia, and the ISC covering the period 1951 to 2019.

We present the bulletin that contains some 20,000 relocated events. We first relocated each event using the single-event location algorithm iLoc and RSTT predictions and identified GT events. Then we relocated the entire seismicity of the Caucasus region with the multiple-event location algorithm Bayesloc, using the iLoc results as initial locations and the GT events as constraints.

We show that each relocation step leads to significant improvements, as indicated by tightening of event clusters. The improved view of the seismicity reveals a narrow band of crustal events along the southern flank of the Greater Caucasus we interpret as a megathrust, and confirms both a region of deep seismicity beneath the northeastern Caucasus and a possible area of slab detachment in the central part of the range.

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On the operation and monitoring of a heterolithic large ring laser: ROMY

DOI: 10.57757/IUGG23-4178 - LINK

Andreas Brotzer[1], Heiner Igel[1], Karl Ulrich Schreiber[2], Jan Kodet[2], Felix Bernauer[1], Joachim Wassermann[1]
[1]Ludwig-Maximilians University Munich, Department of Earth and Environmental Sciences, Munich, Germany
[2]Technical University of Munich, Institute for Astronomical und Physical Geodesy, Munich, Germany

The large ring laser array ROMY (ROtational Motions in seismologY) consists of four Sagnac inferferometers, each representing an individual, high-sensitive rotation rate sensor, joined as a tetrahedral, heterolithic structure, due to its triangular rings of 12 meter side length. This size and the heterolithic construction introduces new challenges in the operation and monitoring of a large ring laser. Currently high performing ring lasers, such as G-ring, are individual, monolithic large ring lasers, that are less affected by mechanical instability, however, suffer from orientation changes that contribute to the variation in Sagnac frequency. Exploiting the full potential of a large ring laser such as ROMY would enable to observe rotational ground motions close to the rotational low noise model. We discuss required steps towards a stable and enhanced performance of the hetherolicitc ring laser array ROMY, especially for seismology and present implemented tilt and environmental monitoring as well as the influence of the signal processing chain on the obtained signals.

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Foreshock characteristics of the 2020 M6.4 Jiashi earthquake

DOI: 10.57757/IUGG23-1454 - LINK

Shiguang Deng[1], *Yanyan Han*[1], *Haikun Jiang*[1]
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Foreshocks could provide valuable information for seismogenic process. Similar to aftershocks and swarms, foreshocks are usually clustered in time and space, which could result in low magnitude earthquakes being overwhelmed by the coda waves of other earthquakes. In addition, the limited observation condition could result in the loss of small earthquakes in local catalog. The waveform correlation technique has been proved to be an effective method to detect missing small earthquakes and widely used in foreshock and aftershock sequence detection. On January 19, 2020, the M_S6.4 earthquake occurred in Jiashi, Xinjiang. About 45 hours before the earthquake, the M_S5.4 earthquake occurred in the focal area, which formed a typical foreshock sequence. In this study, we collected the continuous waveforms between December 1, 2019 and January 31, 2020 from 6 stations located within 100 km of the mainshock. With 791 relocated earthquakes (including 33 foreshocks) as templates, 4664 earthquakes (including 261 foreshocks) were detected and located by the Match & Locate method. The complete magnitude of the catalog was reduced from M_L1.6 to M_L1.0. With the enhanced catalog, we observe that the foreshock sequence has lower *b*-value than aftershocks and lacks small-magnitude (M_L<0.3) events, which are generally consistent with other studies. According to the spatial and temporal evolution of the earthquake sequence, seismicity becomes relative quiet within 26 days before the Jiashi M_S5.4 earthquake and 2 days before the mainshock. In addition, the earthquakes during the two days before the mainshock migrated to the mainshock epicenter.

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Updates on the ISC-GEM Global Instrumental Earthquake Catalogue (1904-2019)

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The first version of the ISC-GEM Global Instrumental Earthquake Catalogue (www.isc.ac.uk/iscgem/index.php) was released in January 2013 (Storchak *et al*., 2013). The goal of the catalogue is to improve the homogeneity (to the largest extent possible, in time and space) of earthquake parameters (e.g., location and magnitude) and list them along with formal uncertainties to facilitate, among others, seismic hazard and Earth's seismicity studies.

Ten years on from the first release, we report on the latest developments of the catalogue following the completion of the Extension (Di Giacomo *et al*., 2018) and Advancement projects (Di Giacomo and Storchak, 2022). We expanded the catalogue with several thousands moderate earthquakes down to ~M5.5 between 1904 and 1959 and earthquakes down to ~M5.0 from 1976. Furthermore, we added over a thousand source mechanisms from the literature for earthquakes that occurred before GCMT began in 1976. Finally, we provide an overview of ongoing activities to further improve the catalogue. These include the use of station data recently digitized from the BCIS bulletins for 1950-1963 (Di Giacomo and Storchak, 2023), the reassessment of MS for hundreds of earthquakes for 1964-1970, and the digitization of the Chinese network bulletins for 1971-1979.

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S01 - Posters - Observational Seismology - Open Session

Evidence for the presence of metastable olivine within subducted oceanic lithosphere in the uppermost lower mantle beneath eastern United States

DOI: 10.57757/IUGG23-4721 - LINK

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Approximately two-thirds of Earth's outermost shell is composed of oceanic plates that form at spreading ridges and recycle back to Earth's interior in subduction zones. A series of physical and chemical changes occur in the subducting lithospheric slab as the temperature and pressure increase with depth. In particular, olivine, the most abundant mineral in the upper mantle, progressively transforms to its high-pressure polymorphs near the mantle transition zone, which is bounded by the 410 km and 660 km discontinuities. However, whether olivine still exists in the core of slabs once they penetrate the 660 km discontinuity remains debated. Based on SKS and SKKS shear-wave differential splitting times, we report new evidence that reveals the presence of metastable olivine in the uppermost lower mantle within the ancient Farallon plate beneath the eastern United States. Such differential splitting times were attributed to anisotropy in the D” layer. Spatial coherency analysis and consistency between the area with differential splitting times and that with higher than normal seismic velocities favor an uppermost lower mantle origin of the differential times. We estimate that the low-density olivine layer in the subducted Farallon slab may compensate the high density of the rest of the slab associated with the low temperature, leading to neutral buoyancy and preventing further sinking of the slab into the deeper part of the lower mantle.

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S01 - Posters - Observational Seismology - Open Session

Similarity analysis for event characterisation in the context of the Comprehensive Nuclear-Test-Ban Treaty (CTBT)

DOI: 10.57757/IUGG23-4151 - LINK

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Monitoring compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) requires reliable seismological methods for event characterisation to identify possible candidate events within a sequence of seismic events, which are possible treaty violations.
National Data Centre (NDC) are the national scientific organizations to advise their governments concerning CTBT monitoring and analysing suspicious events. The German NDC (BGR) regularly organises international NDC Preparedness Exercises (NPE), dealing with fictitious treaty violations to practice the combined analysis of CTBT verification technologies. These exercises help to evaluate the effectiveness of analysis procedures applied at NDCs and the quality, completeness and usefulness of IDC products.
The last exercise - NPE2019 - was a combined waveform-radionuclide scenario. The source region and time domain of a possible treaty violation activity was determined from atmospheric transport modelling (ATM) in backtracking mode with input data from fictitious particulate radionuclide and radioxenon measurements at stations of the International Monitoring System. An earthquake sequence could be identified within the specified source region and time period from ATM analysis. Due to the untypical shallow focal depth of about 3 km and no mining activities, the earthquake sequence in combination with synthetic data is well suited to assess discrimination methods.
Synthetic waveform data, which were modified from real recordings to simulate more explosive like characteristics, are added to the earthquake sequence. A similarity analysis was applied to the combination of fictitious and real waveform data with the objective to identify the fictitious recordings as conspicuous. Various score values were defined to achieve an automatic procedure.

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S01 - Posters - Observational Seismology - Open Session

Seismotectonics of the Shahrud Valley in western Alborz

DOI: 10.57757/IUGG23-0217 - LINK

Mir Ali Hassanzadeh[1], *Esmail Shabanian*[1], *Abdolreza Ghods*[1]
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The Shahrud fault lies in the western Alborz and in the southeast of the sinistral strike-slip Rudbar fault (1990 7.3 Mw Rudbar-Manjil). The surface trace of the Shahrud fault is depicted on the active faults map of Iran as a continuous twisted curve of 65 km in length. Shahrud fault lies in the north of Qazvin and is accounted for a potential source of future destructive earthquakes. 698 local earthquakes have carefully relocated and focal mechanisms were determined for two events. According to the focal mechanisms of earthquakes that occurred in the area between the Rudbar and Shahrud faults, sinistral kinematics is suggested for the western part of the Shahrud fault. The remote sensing analysis of satellite imageries complemented by field measurements allows for revising the fault map of the area. Also, earthquake-related features such as thermal and travertine springs as well as landslides are aligned along the main fault traces of the area indicating the tectonic activity of these deep-seated structures. The kinematics investigation based on seismological and geological data indicates that the Shahrud Valley is affected by a complex fault network comprising a variety of faults with different orientations. The seismicity extended over the area and fault kinematics measured along the fault zones indicate that the Shahrud fault zone is not a simple S-dipping ”thrust fault”, but, is a simplified geological interpretation of an intersection zone produced by kinematic and structural interactions of distinct E-W, NNE- and NW-striking fault trends at the southern flank of the Shahrud Valley.

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S01 - Posters - Observational Seismology - Open Session

Vertical component tilt property of Japanese BBOBS and its implication

DOI: 10.57757/IUGG23-0532 - [LINK]

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Broadband ocean bottom seismometer (BBOBS) is essential instrument to reveal the deep Earth structure so that many seafloor observations by BBOBS have been deployed. It is difficult for BBOBS to make the sensor's level accurate, and this makes a high noise level of vertical component of BBOBS. To reveal the leveling accuracy and its contribution to noise of BBOBS is important to improve the BBOBS design.

We estimated the tilt angle and direction of the vertical component of sensor by applying noise reduction method (Kawano et al., 2023) to more than 80 Japanese BBOBS. The Japanese BBOBS contains all components in the titanium alloy sphere housing, and the sensor (CMG-3T) is installed on the leveling unit.

Estimated tilt angles are 0.02–2.4 degrees (0.9±0.4 degree in average). The direction of tilt is around the NS output of the sensor. The tilt angle and direction are stable during its one-year seafloor observation, and those of the same sensor and leveling unit in different observations are similar , suggesting that estimated tilt is considered to be unique to each sensor unit.

The estimated directions of the tilt are around NS output which is consistent that the vertical component of the CMG-3T is designed to oscillate along NS direction.

The leveling unit to keep it in level within ±0.3º during the observation, however, the estimated tilt are larger than that. One possible explanation of the difference between measured and estimated tilt is that the seafloor current is slightly tilted along with seafloor topography.

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Shear-wave splitting patterns in the Habanero Geothermal Field, Cooper Basin, Australia

DOI: 10.57757/IUGG23-4392 - LINK

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[2]Hellenic Mediterranean University Research Center,
Institute of Physics of Earth's Interior and Geohazards - UNESCO Chair on Solid Earth Phys ics and Geohazards Risk Reduction, Chania, Greece

Upon entering a medium with a strongly anisotropic feature, shear-waves refract and produce two orthogonally polarized waves, travelling with different velocities (the S_{fast} and S_{slow}). The polarization direction of the S_{fast} and the time-delay between the arrivals of the two waves are common metrics to quantify splitting. In the upper crust, anisotropy has been often attributed to stress-sensitive fluid-filled microcracks, whose characteristics may change over time. The Habanero Geothermal Field in Cooper Basin (Australia) is a site of multiple hydraulic stimulation tests, closely monitored by a dense network of 24 surficial and borehole sensors. In the current study, we use a fully automatic analysis scheme to identify shear-wave splitting in waveforms of approximately local 30,000 earthquakes, which occurred in a shallow ~500 m thick sub-horizontal layer. Results indicate a complex state of anisotropy, with both azimuths of faulting and the local maximum horizontal compressive stress component being represented in the measured polarization directions. Time-delay changes present a potential association with the activation of the structure due to the stimulation.

Acknowledgements
The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 00256).

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Comparison of relative locations methods and their accuracy for determining fault structures

DOI: 10.57757/IUGG23-2710 - LINK

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Precise earthquake locations are a prerequisite for determining real fault structures. To improve the precision of the event location, a few relative locations methods are commonly used to refine event locations. Relative relocation methods reduce effects of an imperfect velocity model and errors due to arrival time measurement. We performed comparative tests of three different relocation methods: HypoDD (HD), GrowClust (GC) and Master event (ME). We tested the efficiency and differences in the event locations using these three methods on dataset from REYKJANET seismic network operating in Iceland on Reykjanes Peninsula. All these methods provide substantially focused shapes of clusters compared to the absolute event locations but the locations of individual events differ evidently depending on the method used. We also aimed at an effect of the control parameters of HD, GC and ME on final location results and their optimization as well as computational and memory demands.

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Constraining the spatial distribution of lithospheric and asthenospheric anisotropies beneath Australia using shear wave splitting analyses

DOI: 10.57757/IUGG23-4696 - LINK

Kilun Ba[1], Stephen Gao[2], Jianguo Song[1], Kelly Liu[2]
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[2]Missouri University of Science and Technology, Geology & Geophysics, Rolla, USA

The spatial distribution of seismic azimuthal anisotropy beneath Australia is investigated using splitting of the teleseismic PKS, SKKS, and SKS phases to delineate asthenospheric flow and lithospheric deformation beneath one of the oldest and fast-moving continents on Earth. In total 511 pairs of high-quality splitting parameters were observed at 116 seismic stations. Unlike other stable continental areas in Africa, East Asia, and North America, where spatially consistent splitting parameters dominate, the fast orientations and splitting times observed in Australia show a complex pattern, with a slightly smaller than normal average splitting time of 0.85 ± 0.33 s. On the North Australian Craton, the fast orientations are mostly N-S, which is parallel to the absolute plate motion (APM) direction in the hotspot frame. Those observed in the South Australian Craton are mostly NE-SW and E-W, which are perpendicular to the maximum lithospheric horizontal shortening direction. In east Australia, the observed anisotropy can be attributed to either APM induced simple shear or lithospheric fabric parallel to the strike of the orogenic belts. The observed spatial variations of the azimuthal anisotropy, when combined with results from depth estimation utilizing the spatial coherency of the splitting parameters and seismic tomography studies, suggest that the azimuthal anisotropy in Australia can mostly be related to simple shear in the rheologically transition layer between the lithosphere and asthenosphere. Non-APM parallel anisotropy is attributable to modulations of the mantle flow system by undulations of the bottom of lithosphere, with a spatially variable degree of contribution from lithospheric fabric.

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S01 - Posters - Observational Seismology - Open Session

On the stress dependence of the elastic tensor

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The dependence of the elastic tensor on the equilibrium stress is investigated theoretically. Using ideas from finite elasticity, it is first shown that both the equilibrium stress and elastic tensor are given uniquely in terms of the equilibrium deformation gradient relative to a fixed choice of reference body. Inversion of the relation between the deformation gradient and stress might, therefore, be expected to lead neatly to the desired expression for the elastic tensor. Unfortunately, the deformation gradient can only be recovered from the stress up to a choice of rotation matrix. Hence it is not possible in general to express the elastic tensor as a unique function of the equilibrium stress. By considering material symmetries, though, it is shown that the degree of non-uniqueness can sometimes be reduced, and in some cases even removed entirely. These results are illustrated through a range numerical calculations, and we also obtain linearized relations applicable to small perturbations in equilibrium stress. Finally, we make a comparison with previous studies before considering implications for geophysical forward- and inverse-modelling.

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S01 - Posters - Observational Seismology - Open Session

Geometry of the rivera and cocos plates in western Mexico from local seismicity studies

DOI: 10.57757/IUGG23-0211 - LINK

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A total of 5,220 hypocenters located in the region of Jalisco, Colima and Michoacan states in western Mexico are analysed. We observe that the geometry and seismic characteristics of the subduction at Jalisco Block, Colima Rift Zone and Michoacan Block are different. The contact between the Rivera plate and the Jalisco Block is tectonically complex and can be separated into at least four sections: two located between Bahía Banderas and Purificacion River and the other two between Purificacion River and Colima Rift Zone. South of Bahía Banderas, the slab is observed until 130 km with a dipping angle of 24°. In the Tomatlán River and San Nicolas River areas, the slab is observed until 85 km from the trench dipping 26°, while in the region of Purificacion River, the slab is divided into three segments with different dipping angles, up to 140 km from the trench. In the area of the Marabasco River, the slab can be observed in two segments, with dip angles of 26° and 35°, respectively, and up to 145 km from thrench. There is no evidence of a slab below the Colima Rift Zone due to seismicity being scarce, except in the Colima Volcano area and on the coast, where deep earthquakes (> 70km) are below Colima Volcano that could be associated with the volcano. The crustal thickness in the Michoacán Block is 30 km. To the south, the Cocos Plate dips between 24° and 30° and is slightly bent in the west direction.

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Seismic imaging of the crust and upper mantle beneath eastern Dominican Republic and Muertos Trough

DOI: 10.57757/IUGG23-4767 - LINK

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The oblique convergence between the Caribbean and North American plates produces a tectonic collage in Hispaniola Island, where Muertos Trough marks the trace of a low-angle thrust fault bounding an accretionary wedge. In this work, we analyzed the seismic data corresponding to Profiles C and D of the CARIBE NORTE project (2009) in the frame of the current KUK ÀHPÁN and MICROSIS-I projects. A seismic array of vertical and three-component land stations registered these profiles along N-S and W-E seismic transects of 350 and 450 km, respectively. The seismic sources in these lines corresponded to land borehole explosions 1 Ton (S1, S2, and S3), three marine shooting lines (LM3N, LM3S for Profile C and LM4, for Profile D), and one earthquake that occurred during the registering period.

We constrained the seismic structure of the Dominican Republic by the inversion of wide-angle seismic travel-time data for the previous 2D P-wave velocity model of both profiles. In the eastern zone, the Moho discontinuity rises to 24 km deep. In comparison, it increases towards the island's interior with a maximum depth value of approximately 30 km deep in the west and central part of the transect. The analysis of Profile C shows the deformation produced by Muertos Trough and Muertos Thrust Belt over San Pedro Basin and eastern Hispaniola Island.

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Low seismic velocity anomalies marking the active faults of the lebanese restraining bend and the mount-Lebanon thrust

DOI: 10.57757/IUGG23-0027 - LINK

Mohamed Salah[1]
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The Lebanese Restraining Bend (LRB) comprises the NNE-trending Mount Lebanon and the NE Anti-Lebanon ranges which are separated by the Bekaa Valley. Offshore, an east-dipping thrust fault system (the Mount-Lebanon Thrust, MLT) faces the coastal strip between Saida and Arqa. Historical earthquakes with casualties are documented along these active faults in the Eastern Mediterranean. We apply a seismic tomography method to P- and S-wave arrival times retrieved from the ISC seismological bulletins to determine the 3-D seismic velocity structure of the crust and uppermost mantle beneath this region. The seismic data set was generated by carefully selected events which are recorded by at least five stations and all unreliable arrivals have been excluded before the final tomographic inversion. We adopted an initial P-wave velocity model for the tomographic inversion, while the initial S-wave velocity model was computed using an Vp/Vs ratio of 1.725 derived from a wadati diagram. From the obtained P- and S-wave velocity models, we determined the Vp/Vs ratio for a better interpretation of the velocity anomalies. Lateral heterogeneities in the study area are clearly visible. Low velocity anomalies are revealed along the surface traces of the LRB and offshore along the MLT. Average to high Vp/Vs anomalies are clearly detected at lower crustal levels. Results of the checkerboard resolution test and the ray path coverage indicate that the velocity and Vp/Vs anomalies are reliable features. The present observations are compatible with many seismological and geological features detected beneath the Eastern Mediterranean.

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S01 - Posters - Observational Seismology - Open Session

The Transnational access and training within the Geo-INQUIRE EU project to develop leading-edge science at facilities and test-beds across Europe

DOI: 10.57757/IUGG23-4427 - LINK

Gaetano Festa[1], Shane Murphy[2], Marius Majdanski[3], Iris Christadler[4], Fabrice Cotton[5], Angelo Strollo[5], Marc Urvois[6], Volker Rohling[7], Stefano Lorito[8], Andrey Babeyko[5], Daniele Bailo[8], Jan Mickalek[9], Otto Lange[10], Javier Quinteros[5], Mateus Prestes[5]
[1]Università di Napoli Federico II, Fisica "Ettore Pancini", Napoli, Italy
[2]Ifremer, ALéas MArins, Brest, France
[3]IG-Pas, Geophysics, Krakow, Poland
[4]LMU, Earth and Environmental Sciences, Munich, Germany
[5]GFZ, Geophysics, Postdam, Germany
[6]BRGM, French Geological Survey, Orleans, France
[7]NTNU, Energy and Process Engineering, Gløshaugen, Norway
[8]INGV, Osservatorio Nazionale Terremoti, Roma, Italy
[9]University of Bergen, Geophysics, Bergen, Norway
[10]University of Utrecht, Geosciences, Utrecht, Netherlands

The Geo-INQUIRE (Geosphere INfrastructure for QUestions into Integrated REsearch) project, supported by the Horizon Europe Programme, is aimed at enhancing services to allow data, products and software to be accessible to the Geoscience scientific community.

In the framework of Geo-INQUIRE, Transnational Access (TA, both remote and physical) will be provided at six test beds across Europe:the BedrettoLab, Switzerland; the Ella-Link Geolab, Portugal; the Liguria-Nice-Monaco submarine infrastructure, Italy/France; the Irpinia Near-Fault Observatory, Italy; the Eastern Sicily facility, Italy; and the Corinth Rift Laboratory, Greece. These test beds are state-of-the-art research infrastructures, covering the Earth's surface, subsurface, and marine environments over different spatial scales, from small-scale experiments in laboratories to kilometric submarine fibre cable. TA will be also offered for software and workflows belonging to the EPOS-ERIC and the ChEESE Centre of Excellence for Exascale in Solid Earth. TA are grounded on simulation of seismic waves, tsunamis and landslides. Geo-INQUIRE will grant TA to researchers to develop their own experiments with the aim of advancing scientific knowledge of Earth processes while fostering cross-disciplinary research across Europe. To be granted, researchers submit a proposal to the yearly TA calls that will be issued three times during the project life. Calls will be advertised at the Geo-INQUIRE web page https://www.geo-inquire.eu/ and through the existing community channels. The first call is expected to be issued in Fall 2023.The proposals, for both TA and training, will be evaluated by a panel that reviews the technical and scientific feasibility of the project.

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S01 - Posters - Observational Seismology - Open Session

Regional and global characteristics of observable foreshocks

DOI: 10.57757/IUGG23-1195 - LINK

Nadav Wetzler[1], Emily Brodsky[2], Esteban Chaves[3], Thomas Goeble[4], Thorne Lay[2]
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[2]University of California Santa Cruz, Department of Earth and Planetary Sciences, Santa Cruz, USA
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[4]University of Memphis, Center for Earthquake Research and Information, Memphis, USA

Regional and global variations of foreshock occurrence are systematically examined using earthquake from eight regional catalogs (Italy, Southern California, Northern California, Costa Rica, Onshore Japan, Alaska, Turkey, and Greece) with $M_C \geq 3.0$, and the one global catalog (NEIC) with $M_C \geq 5.0$.

For most of the catalogs (excluding Italy and Southern California) the measured *b-values* of the foreshocks of all region-specific mainshocks are lower by 0.1 to 0.2 than *b*-values of respective aftershocks. Estimates of foreshock probabilities for each mainshock are method-dependent; however, consistent regional trends exist regardless of method. Variations in foreshocks show relatively high probabilities of having at least one foreshock in Italy (~43-56%), compared with other regional catalogs that decrease to 14-41% for regions such as Turkey, Greece, and Costa Rica. Some regions with relatively high background seismicity have comparatively low probabilities of detectable foreshock activity when using methods that account for variable background, possibly due to depletion of near-failure fault conditions by background activity. At a global scale, foreshock rates are similar to regional values with range of 14% to 43% of large mainshocks having at least one foreshock, but a narrower range of 13% to 25% having at least one foreshock with magnitude within two units of the mainshock magnitude. Global variation demonstrates that the western circum-Pacific is prone to having more foreshock activity than the eastern circum-Pacific. The fact that areas having more frequent foreshock activity also have relatively high aftershock productivity suggests common conditions promoting foreshocks and aftershocks.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Adapting an existing seismic network to the earthquake early warning mission – southern California experience

DOI: 10.57757/IUGG23-2977 - LINK

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[1]*U. S. Geological Survey, Earthquake Science Center, Pasadena, USA*
[2]*California Institute of Technology, Geophysics and Planetary Sciences, Pasadena, USA*

Earthquake early warning (EEW) for California was initially conceived as a faster version of normal seismic network operations. For the Southern California Seismic Network (SCSN) this early view has been found to be well short of reality. We review lessons SCSN learned through implementation of the ShakeAlert EEW system on the west coast of the United States.

EEW-based adaptations affect stations, telemetry, and data acquisition, processing and archiving. Station coverage in the SCSN was good at the start of EEW implementation but 5+ years of permitting and station installations have been required to reduce EEW detection times to target levels. SCSN started with an advantage not all ShakeAlert networks enjoyed as installed dataloggers could stream the 1-second data packets needed for low data latency. Telemetry priorities can differ between EEW and normal network operations. EEW can only use low-latency data; network operators want complete data to simplify archiving and can accept some latency. EEW only requires three channels of strong-motion data; networks prefer 6 channels, with velocity data. We found that during strong earthquake shaking some links could not support both and developed severe latency. To meet both requirements, telemetry links are now being re-engineered. Multicasting is needed to allow waveform data to be shared across multiple servers for redundant processing. EEW algorithms require separate waveform processing and trigger detection. Specialized algorithms are also required to estimate magnitudes from limited P-wave amplitude data. While similar in appearance, EEW places unique and unanticipated demands on our regional seismic network.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

CEEIN: The Central and Eastern European Infrasound Network

DOI: 10.57757/IUGG23-1624 - [LINK]

István Bondár[1], *Tereza Šindelářová*[2], *Daniela Ghica*[3], *Ulrike Mitterbauer*[4], *Alexander Liashchuk*[5], *Cristian Neagoe*[3], *Marcell Pásztor*[6], *Jiří Baše*[2], *Jaroslav Chum*[2], *Constantin Ionescu*[3], *Barbara Czecze*[7], *Alexis Le Pichon*[8]
[1]*Research Centre for Astronomy and Earth Sciences- ELKH, Institute for Geological and Geochemical Research, Budapest, Hungary*
[2]*Institute of Atmospheric Physics, The Czech Academy of Sciences, Prague, Czech Republic*
[3]*National Institute for Earth Physics, x, Magurele, Romania*
[4]*Zentralanstalt für Meteorologie und Geodynamik, x, Vienna, Austria*
[5]*Main Centre of Special Monitoring, National Center for Control and Testing of Space, Kiyv, Ukraine*
[6]*Eötvös Loránd University, Institute of Geography and Earth Sciences- Department of Geophysics and Space Science, Budapest, Hungary*
[7]*Institute of Earth Physics and Space Science, Kovesligethy Rado Seismological Observatory, Sopron, Hungary*
[8]*CEA/DAM/DIF, x, Arpajon, France*

The Central and Eastern European Infrasound Network (CEEIN) established in 2018 as the collaboration between the Zentralanstalt für Meteorologie and Geodynamik, Vienna, Austria; the Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czech Republic; the Research Centre for Astronomy and Earth Sciences of the Eötvös Loránd Research Network, Budapest, Hungary; the National Institute for Earth Physics, Magurele, Romania and the Main Centre of Special Monitoring National Center for Control and Testing of Space Facilities, State Agency of Ukraine. Waveform data of the CEEIN stations are archived at the NIEP EIDA node, and can be downloaded from www.ceein.eu.

We show that CEEIN improves infrasound event detection capabilities in Southern and Eastern Europe, and demonstrate that adding infrasound observations to seismic data in the location algorithm improves location accuracy. We identify coherent noise sources observed at CEEIN stations. We present the bi-annual CEEIN bulletin of infrasound and seismo-acoustic events, our contribution to the European infrasound catalogue. Many of the events in the CEEIN bulletin are ground truth events that can be used in the validation of atmospheric models and infrasound raytracing algorithms.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Overview of ORFEUS Data Services and Activities to Integrate Access to Seismic Waveform Data in the Euro-Mediterranean Region

DOI: 10.57757/IUGG23-3573 - LINK

Carlo Cauzzi[1], *Jarek Bieńkowski*[2], *Wayne Crawford*[3], *Susana Custódio*[4], *Sebastiano D'Amico*[5], *Christos Evangelidis*[6], *Christian Haberland*[7], *Florian Haslinger*[8], *Anastasia Kiratzi*[9], *Petr Kolínský*[10], *John Clinton*[11], *Zafeiria Roumelioti*[12], *Karin Sigloch*[13], *Reinoud Sleeman*[2], *Angelo Strollo*[14]

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[2]ORFEUS Data Center ODC and Royal Netherlands Meteorological Institute KNMI, R&D Seismology and Acoustics,
ORFEUS Data Center ODC and Royal Netherlands Meteorological Institute KNMI- De Bilt, Netherlands
[3]Institut de Physique du Globe de Paris IPGP, Marine Geosciences, Paris, France
[4]Faculty of Sciences of the University of Lisbon FCUL, Instituto Dom Luiz IDL, Lisbon, Portugal
[5]Faculty of Science- University of Malta, Department of Geosciences, Valletta, Malta
[6]National Observatory of Athens NOA, Institute of Geodynamics, Athens, Greece
[7]GFZ German Research Centre for Geosciences, Geophysical Imaging, Potsdam, Germany
[8]EPOS Seismology and ETH Zürich, Swiss Seismological Service SED, Zürich, Switzerland
[9]EPOS Seismology and Aristotle University of Thessaloniki AUTH, Department of Geophysics, Thessaloniki, Greece
[10]Czech Academy of Sciences IG-CAS, Institute of Geophysics, Prague, Czech Republic
[11]ETH Zürich, Swiss Seismological Service SED, Zürich, Switzerland
[12]University of Patras, Department of Geology, Patras, Greece
[13]Université Côte d'Azur, Laboratoire Géoazur, Sophia Antipolis, France
[14]GFZ German Research Centre for Geosciences, Seismology, Potsdam, Germany

ORFEUS (Observatories and Research Facilities for European Seismology, orfeus-eu.org) coordinates and promotes seismology in the Euro-Mediterranean region through harmonized collection, archival and distribution of seismic waveform data & metadata, based on services and products managed at national level by more than 60 participating seismological Institutions. ORFEUS is one of the founding members of EPOS Seismology (www.epos-eu.org/tcs/seismology) and its services are largely integrated in the EPOS Data Access Portal (www.ics-c.epos-eu.org). ORFEUS comprises: (i) the European Integrated waveform Data Archive (EIDA; orfeus-eu.org/data/eida); (ii) the European Strong-Motion databases (orfeus-eu.org/data/strong); and iii) the recently established group representing the community of European mobile pools, including amphibian instrumentation (orfeus-eu.org/data/mobile). Currently, ORFEUS facilitates access to the waveforms acquired by more than 18,000 stations including dense temporary experiments (e.g., AlpArray, AdriaArray), with strong emphasis on open, high-quality data. Access to data and products is ensured through state-of-the-art technologies - with strong emphasis on web services - clear policies and licenses, and acknowledging the crucial role played by data providers. Significant efforts are underway to enhance the existing services to tackle the challenges posed by the Big Data Era and the needs of computational seismology, and to actively encourage interoperability and integration of

multidisciplinary datasets in geoscience workflows. ORFEUS also implements community services that include software and travel grants, webinars, workshops, editorial initiatives and discussion forums. ORFEUS activities are assessed and improved through the interaction with a User Advisory Group, which comprises European Earth scientists with expertise on a broad range of disciplines.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

GeoNet Aotearoa New Zealand Station Metadata: Managing multidisciplinary instrument and deployment meta-data using a source code versioning system

DOI: 10.57757/IUGG23-3227 - LINK

Mark Chadwick[1], Elisabetta D'Anastasio[1], Jerome Salichon[1], Conrad Burton[1], Steve Sherburn[1], Sam Taylor-Offord[1], Muriel Naguit[1], Megan Madley[1], Richard Guest[1], Jonathan Hanson[1], GeoNet Programme Team[1]
[1]GNS Science, Data Science & Geohazards Monitoring, Lower Hutt, New Zealand

GNS Science Te Pū Ao, through its GeoNet programme, operates a multidisciplinary sensor network to monitor geological hazards in Aotearoa New Zealand. Data from more than 800 permanent monitoring sites are continuously collected, transformed and delivered to a range of end users.

Managing multidisciplinary instrument metadata is a key task of the GeoNet datacentre. In 2017 GeoNet moved away from using a corporate relational database to using a modern and novel approach to manage metadata. All of this metadata is freely available and treated as a dataset (DOI: 10.21420/0VY2-C144) to give users access to whatever metadata they need and to improve visibility and usability.

This system is at the core of the GeoNet data pipeline and allows the data transformation process, from the field to end users, to be automated. The system uses a software development approach: a code versioning system based on git and hosted at "github.com/GeoNet/delta" which allows instrument metadata and their changes in time to be peer reviewed, version controlled and checked for consistency. Equipment and installation details are stored as a set of CSV files and short XML seismic response file segments. This allows for easy access and maintenance, with no proprietary external software needed to decode or examine the information.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Implementation of SAW method in GIS for determining the suitable position for seismological stations in Zadar County

DOI: 10.57757/IUGG23-1758 - LINK

Vedran Damjanović[1], Valentina Gašo[1], Stijepo Grljević[1], Marko Kapelj[1], Iva Kostanjšek[1], Viktorija Milec[1], Marko Pervan[1], Anamarija Tremljan[1], Antonio Brcković[1], Tomislav Fiket[1]
[1]Faculty of Science- Geophysical Department, Croatian Seismological Survey, Zagreb, Croatia

After the devastating earthquakes in Petrinja in December 2020, the Croatian Seismological Survey started the CROSSNET project, whose goal is to improve and expand the existing network of seismological stations in the Republic of Croatia with 95 new seismic stations.

The area of study is Zadar County, the northern part of the Dalmatia Region. The Mediterranean karst terrain requires a different approach when determining the criteria for setting up seismological stations, unlike the Croatian part of the Pannonian basin.

The simple additive weighting method (SAW), also known as the weighted linear combination or scoring method, was used to derive suitability maps for field surveys to find optimal locations for seismological stations. It uses experts' opinions to derive weights for each criterion relative to one another, as well as values for each criterion raster. The score for each alternative (pixel in raster GIS) regarding every criterion was calculated by multiplying the normalized weight of relative importance for each criterion (which is assigned by the decision maker) and the standardized values for each criterion raster. The suitability index for each alternative which represents the final suitability map is a sum of the scores of every criterion raster for each alternative.

Limiting factors of this method are assumptions of linearity and additivity in solving the spatial problem in question but it offers an uncommon GIS approach for seismological network planning.

This work has been fully supported by Next Generation EU and National Recovery and Resilience Plan under project C6.1. R4-I1.

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to one another, as well as values for each criterion raster. The score for each alternative (pixel in raster GIS) regarding every criterion was calculated by multiplying the normalized weight of relative importance for each criterion (which is assigned by the decision maker) and the standardized values for each criterion raster. The suitability index for each alternative which represents the final suitability map is a sum of the scores of every criterion raster for each alternative.

Limiting factors of this method are assumptions of linearity and additivity in solving the spatial problem in question but it offers an uncommon GIS approach for seismological network planning.

This work has been fully supported by Next Generation EU and National Recovery and Resilience Plan under project C6.1. R4-I1.

S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Earthquake occurrence characteristics in the Kefalonia Transform Fault Zone (KTFZ), Greece

DOI: 10.57757/IUGG23-0268 - LINK

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The Kefalonia Transform Fault Zone (KTFZ) extends for more than 150 km offshore the western coastlines of Kefalonia and Lefkada Islands being one of the largest sources of seismic hazard in Greece. Since the occurrence of the 2003 Lefkada M_w6.3 main shock, continuous seismic monitoring was intensified in this area, by firstly installing temporary digital seismological stations, and then by transforming this network into a permanent one and incorporating the stations in the Hellenic Unified Seismological Network (HUSN). The network was improved and currently accounts twelve (12) stations in the two Islands, along with five (5) in the nearby Ionian Islands. Microseismicity is continuously monitored; manual phase picking is performed for earthquake as small as M1.2, and relocated for the compilation of a highly accurate earthquake catalogue. Earthquake focal mechanisms are determined by waveform modelling and first polarities, and are exploited along with the highly accurately relocated seismicity for the identification of the local active structures and in particular the geometry and kinematic of the minor fault segments. From the seismicity and fault plane solutions analysis we integrated the major physical features of the regional seismotectonics and suggested a comprehensive seismotectonic model that improves our understanding and must be considered in any seismic hazard model.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission – Euratom. Neither the European Union nor the granting authority can be held responsible for them.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Building the ERMES web platform for preparing strong-motion event reports from ITACA and ESM data and metadata

DOI: 10.57757/IUGG23-4132 - LINK

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[1]*Instituto Nazionale di Geofisica e Vulcanologia, Milano Section, Milano, Italy*

The exponential growth of seismic networks, at regional, continental and global levels, and the availability of online transmission of large volumes of data in near-real time, allows us to analyze the ground motion of an earthquake, of low or high magnitude, in very short times with high levels of confidence. This was the case of the recent seismic sequences in Italy (2022-11-09 Mw 5.6 Ancona) and Middle East (2023-02-06 Mw 7.8 Turkey-Syria), when thousands of researchers worldwide contributed to providing rapid analyses of seismic motion to support emergency activities and physical understanding of the observed phenomenon during the sequence.

In this work, we present the new web-tool ERMES (Earthquake Reports of strong Motion EStimation) designed to create an event-report describing the characteristics of the ground motion associated with a seismic event. It is integrated with the Italian (ITACA) and the Engineering Strong Motion (ESM) databases. ERMES is developed as a tool for the analysis of the Intensity Measures soon after an event has occurred, that is reviewed and updated by expert users as new data become available and/or particular aspects of shaking need to be highlighted. In case of past events, ERMES is also useful to study the spatial distribution of the strong motion parameters.

ERMES is the result of the collaborative effort of two INGV institutional tasks, namely the the INGV Seismic Hazard Center and the WP9.3 (Data and reports during the seismic emergency) of the DPC-INGV 2022-2025 Agreement.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Earthquake monitoring in Italy: integration of a temporary seismic experiment into national real-time surveillance, the example of FocusX temporary land-network

DOI: 10.57757/IUGG23-0947 - LINK

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[2]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa, Italy
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[4]Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Rende, Italy
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[6]Università Della Calabria, Laboratorio di Sismologia, Rende, Italy

The INGV is the operational center for earthquake monitoring in Italy, it operates the Italian National Seismic Network and other networks at different scales and is a primary node of EIDA for archiving and distributing seismic recordings. INGV provides earthquake information to the Department of Civil Protection and to the public.

In the frame of the FOCUS (Fiber Optic Cable Use for seafloor studies of earthquake hazard and deformation) project, we deployed a temporary seismic network, FXLand (1J), for a passive seismological experiment to record regional seismicity and teleseismic events. This experiment aims to improve the detection of seismicity; the accuracy of earthquake locations, and to define the crustal structure of the region. The FXLand network (https://doi.org/10.13127/SD/O5QWM6WJCD) is integrated in real-time into the INGV surveillance system. In the deployment period 23rd December 2021- 2nd February 2023, 1186 regional events were located and 153 6+ teleseismic earthquakes occurred (terremoti.ingv.it). We present the analysis of three seismic sequences: one starting on December 23rd 2021 with a magnitude 4.3 near Catania lasting about ten days, one occurred in the Messina Strait on May31st June 1st 2022, the third one in the Ionian Sea from February to April 2022. We applied a template matching technique which doubled the number of detected events in the first two sequences; for the seismicity in the Ionian Sea, to improve detection and locations we are awaiting the data from the FXOBS (XH), a network of broadband and short period OBSs deployed in the Ionian Sea.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Italian 24/7 real-time earthquakes and tsunamis monitoring system

DOI: 10.57757/IUGG23-4439 - [LINK]

Laura Scognamiglio[1], Fabrizio Bernardi[1], Andrea Bono[1], Sergio Bruni[1], Valentino Lauciani[1], Matteo Quintiliani[1], Paolo Bacchi[1], Giorgio Maria De Santis[1], Andrea Di Benedetto[1], Mariangela Trotta[1], Alessandro Amato[1], Lucia Margheriti[1], Alessio Piatanesi[1], Salvatore Stramondo[1]
[1]Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Roma, Italy

The Istituto Nazionale di Geofisica e Vulcanologia (INGV) has the primary responsibility for the seismic surveillance service of the Italian territory and the tsunami alert in the Mediterranean Sea.

The activities in the monitoring room at the INGV National Earthquake Observatory headquarters in Rome (hereafter INGV-Rome), are carried on by two seismologists, one tsunami specialist and one technician/engineer who work in three shifts a day to provide monitoring service on a 24/7 basis. They calculate, as rapidly and accurately as possible, the location and size of all Italian earthquakes with M2.5+ and swiftly disseminate such information to emergency authorities, to government agencies, to the public and the media by different platforms (email, text message, and via Facebook and Twitter). Starting with hypocentral and magnitude parameters, the moment tensors, the historical seismicity map and the shakemaps are also published in (near) real time.

In addition, the INGV-Rome monitoring room hosts the Italian Tsunami Alert Center (CAT-INGV). CAT-INGV is one of the Tsunami Service Providers acting in the North-eastern Atlantic, the Mediterranean and connected sea (NEAM) region of the Intergovernmental Oceanographic Commission (IOC)/UNESCO and is responsible for monitoring the seismicity of the Mediterranean Sea and disseminating tsunami alert messages to member States and EU agencies subscribing its services. The operation and the performance of the INGV monitoring system is ensured by a dedicated research and IT staff who facilitate real-time waveform acquisition and distribution, develop real-time seismic processing systems and new processing algorithms.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

The seismic network of the Valencian Community

DOI: 10.57757/IUGG23-3411 - LINK

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[1]Universidad de Alicante, Earth and Environmental Sciences, Alicante, Spain
[2]Universidad de Alicante,
Departamento de Física- Ingeniería de Sistemas y Teoría de la Señal, Alicante, Spain
[3]Universidad de Alicante, Fisica Aplicada, Alicante, Spain

Spain is a country politically divided in states (communities). In the Comunidad Valenciana (Valencian Community, one of these states), after the enact of Law 2/2020 of the Generalitat Valenciana, the Institut Cartogràfic Valencià acquires responsibility for the creation and maintenance of the Valencian Community Broadband Seismic Network. This network has been created from the already existing Seismic Network of the University of Alicante (RSUA) and cover the entire territory of the Valencian Community. The objective of the Valencian Community Broadband Seismic Network, fully operational since the last quarter of 2022, is to serve as a portal for information and awareness of the seismic phenomenon in the community, as well as to provide useful scientific information for all those research groups interested in seismicity and the active tectonics in the Valencian Community.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net) : Contribution to Early Detection of Seismic Waves and Tsunamis

DOI: 10.57757/IUGG23-2195 - LINK

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[1]*National Research Institute for Earth Science and Disaster Resilience, Network Center for Earthquake Tsunami and Volcano, Tsukuba, Japan*
[2]*The University of Tokyo, Earthquake Research Institute, Tokyo, Japan*

The Philippine Sea plate is subducting from the Suruga and Nankai troughs beneath southwest Japan. Great interplate earthquakes occurred repeatedly along the troughs. In the near future, Nankai trough earthquake will occur and be possible to become nationwide disaster. Early detection of seismic waves and tsunamis by instrument observation is important in order to reduce earthquake and tsunami disaster and one of the advantages of the earthquake and tsunami observation on the seafloor contributes to early detection of them compared to inland observation. The sea area from the off the Kochi Prefecture to Hyuga-nada, which is correspond to the western half of the focal region of the anticipated Nankai trough earthquake, is a blank area of the seafloor observation networks. In 2019, the National Research Institute for Earth Science and Disaster Resilience started a project to develop the Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net) in this blank area. The N-net has two systems, a coastal system and an offshore system, to ensure redundancy, with 18 observation nodes in each system. In this study, we investigated how fast the direct detection of seismic waves and tsunamis can be achieved when N-net data can be acquired. We conducted the calculation of the travel time for seismic waves and tsunamis by assuming point sources. As a result, we found the detection of seismic wave and tsunami was expected to be earlier approximately 20 seconds and approximately 20 minutes at the maximum considering the N-net data, respectively.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Earthquake emergencies in Italy: SISMIKO operational task force for seismic networks rapid deployments and integration in the monitoring system

DOI: 10.57757/IUGG23-3481 - LINK

Milena Moretti[1], *Ezio D'Alema*[2], *Simone Marzorati*[1], *SISMIKO Team and BSI Working Group*
SISMIKO TEAM and BSI Working Group
[1]*Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Roma, Italy*
[2]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano, Milano, Italy*

SISMIKO is the operational task force at the Istituto Nazionale di Geofisica e Vulcanologia aiming at the rapid deployment of temporary seismic stations in the area hit by a significant earthquake or a seismic sequence causing concern and interest with impact on people. Decreasing the average distance between the seismic stations improves network detection, accuracy of the earthquake locations, shakemaps and strong motion parameters.

The data acquired by SISMIKO are available, without any constraints, to the entire scientific community through the EIDA portal Italy node, which assures a high level of data quality.

A national diffusion of the preconfigured seismic stations in different headquarters and a ready acquisition system, guarantee rapid response after an earthquake and allow the immediate acquisition of the data as soon as each seismic station is installed. An international FDSN network code is registered in advance and a five char codification for the station names is applied to request the ISC station codes (T<emergency identifier><headquarter identifier>).

The last emergency (no. 17) in 2022 was caused by an earthquake of Mw 5.5 in the Costa Marchigiana region, where we installed eight stations of the Y1 network the same day as the mainshock (DOI: 10.13127/SD/TBLKBA-3U6).

We present the organization and the objectives of the SISMIKO operational group and the analysis of the dataset of the latest seismic sequence carried out by the seismic surveillance service, the Italian Seismic Bulletin (BSI) and SISMIKO.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Improving real-time monitoring in Târgu-Jiu Area, Romania

DOI: 10.57757/IUGG23-4065 - LINK

Cristian Neagoe[1], *Eduard Nastase*[1], *Constantin Ionescu*[1]
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In February 2023, a seismic sequence started with two strong earthquakes occurring on 13 February with Ml = 5.2 and on 14 February with Ml = 5.7 followed by over 500 aftershocks. Therefore, complex measurements took place in the epicentral area and the nearby regions shortly after the sequence started. In order to increase the quality of locations and record low-magnitude events, new seismic stations were installed in the area. The stations are equipped with broadband sensors (CMG40T), short-period sensors (Mark L4C) and accelerometers (Episensor). The recorded data is sent to the National Data Center for analysis in real time. The processing software used by the Romanian Seismic Network is Antelope. Before processing, all the stations are evaluated to check the performance and data quality. We can calculate the Power Spectral Densities (PSD) and Probability Density Functions (PDF) by analyzing the waveform data and the instrument response files. In addition to the seismic stations, two GNSS mobile stations were installed. One Leica GR50 receiver that replaced the old one on our reference GNSS station TIMA in order to have real-time data from the Velocity and Displacement Engine (VADASE system) at 10 Hz integrated into it. The second one was a new installation, with the same capabilities, both being capable and recording static High-Frequencies measurements to determine the crustal deformation rate and direction within the area.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

PNSN: A regional seismic network and so much more!

DOI: 10.57757/IUGG23-4873 - [LINK]

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[1]*Pacific Northwest Seismic Network, UW Dept of Earth and Space Sciences, Seattle, USA*

Regional seismic networks play an extremely important role in both the seismic coverage of a nation, but also in the education, outreach, and science support of that region. The proto-Pacific Northwest Seismic Network (PNSN) started out in the late 1960s to improve seismic-monitoring coverage after several M>6 earthquakes in 30 years in the US state of Washington. Over the decades, the network grew in both number of stations and geographical coverage as well as adding significant items of scope that are harder to quantify such as communicating with the press and proactively educating the public about hazards and seismic safety. Today the PNSN uses data from over 650 seismic stations (~ 560 that we operate and maintain). We share 100% of our data and earthquake catalog with scientists and the public, contribute to the ShakeAlert Earthquake Early Warning program, maintain active social media presences, give presentations at workshops, libraries, and community centers in addition to hosting onsite tours of school children and adults in our Seismology Lab. But the challenges are still great with respect to obtaining funding, fighting misinformation, and attempting to stay relevant when earthquakes happen on geologic timescales, but American minds are growing more accustomed to TikTok-length stories to fill up the daily infotainment void. This presentation will discuss the strategy for success: leveraging the strengths of graduate student work, the creativity of our undergraduate workers, the determination and persistence of the full-time staff, and the knowledge resources of our fellow regional networks across the United States.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

New Zealand GeoNet multi-hazards Sensor Network: A walk through data products and services for landslide, tsunami, earthquake and volcano monitoring

DOI: 10.57757/IUGG23-0320 - LINK

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Aotearoa-New Zealand islands present some of the world largest seismicity, intense deformation, and volcanic activity. In this environment, GNS Science - Te Pū Ao implements the GeoNet programme since 2001 to satisfy needs and requirements for identification, study, preparedness, and mitigation of frequent geological hazards. With a wide range of air pressure, coastal and deep-sea level sensors, cameras as well as numerous GNSS, seismometers and accelerometers, GeoNet teams not only manage, collect, process, and archive hundreds of instruments but also implement a diversity of services and publicly distribute and maintain open data products. The GeoNet programme aims at enhancing New-Zealand hazard information by continuously developing, integrating, and upgrading its sensor networks and related tools: Instrumentation Database, field instrumentation QC applications, seismic network capability assessment tools, automated updating services etc…The resulting processed information is distributed through high performance and resilient web-services, alerting applications, data streams (real time and archives). In addition, near real-time and curated data products such as strong motion parameters, slow slip observations or eruption detection systems are provided to scientists and public, infrastructure, emergency management and governmental agencies. We present a summarizing assortment of GeoNet data, services and products sourced from more than 20 years of programme implementation. We describe challenges to maintain the current systems, ensure the resiliency, operational status and enable evolving observation methods, products, and services, to integrate new instrumentation types along with strict requirements for 24/7 national geohazard monitoring and for operational science during routine and significant event response.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

A global overview on the application of urban seismic networks

DOI: 10.57757/IUGG23-3433 - LINK

Salvatore Scudero[1], Antonio Costanzo[1], Antonino D'Alessandro[1], Giovanni Vitale[1]
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Local-scale seismic networks within urbanized areas have been usually employed for short-living seismological experiments or studies. However the possibility, to install permanent (or long-term) earthquake monitoring networks within urban contexts began in the mid '90s.

If, from one hand, this possibility was certainly boosted by the support coming from technological developments (digital devices for acquisition and transmission), from the other, the necessity was also driven by the recent global expansion of many urban centers into large metropolitan areas. Also the awareness of the seismic risk in urban center resulted in the increasing interest in the monitoring these areas, with particular focus the most exposed or the most vulnerable ones.

Earthquake monitoring networks especially designed may reveal important tools for several tasks related to the seismic phenomena: from earthquake warnings, to emergency operational tasks during emergencies, or scientific studies. In this paper we refer to such earthquake networks as "Urban Seismic Networks" (USN).

Because of the increasing resorting USNs for several applications, we consider useful to provide a comprehensive view of the state-of-the-art of the use of USNs, looking at their global distribution and objectives but, most of all, at their design and at their technical characteristics. We retrieved information about 71 USNs worldwide.

The USN objectives, as well the other characteristics, have been classified into prearranged groups in order to provide to easily synthesize the various features of the USNs. This review will represent a reference and a guideline for future implementation of USNs.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Considerations on some country-scale earthquake monitoring networks

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Salvatore Scudero[1], *Antonino D'Alessandro*[1], *Anna Figlioli*[2]
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[2]*Universita' di Palermo, Dipartimento di Scienze della Terra e del Mare, Palermo, Italy*

In the last decades each nation, especially those with high seismic risk, has up-graded its seismic network to keep it up with the state-of-the-art criteria. Here we perform the evaluation and a comparison between some the national seismic networks, to evaluate their coverage and their capabilities. We show example from Italy, Greece, Taiwan and New Zealand. For our analysis, we consider the spatial distribution of the nodes of the network together with the ancillary information related to the aims of the network itself (e.g. earthquakes' distribution, seismic hazard, population, distribution on completeness magnitude). Such evaluation is performed with a statistical approach which includes descriptive spatial statistics in combination with point pattern techniques. We are able to highlight the strong points and the drawbacks for each of the considered earthquake monitoring network. Finally this approach helps in addressing future developments for the considered networks.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Field evaluation of newly developed MEMS technology silicon resonant sensor for seafloor pressure observation

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Seafloor pressure observations mainly use precise quartz resonant sensors at the present due to its high sensibility. Recently, a new silicon resonant sensor using Micro Electro Mechanical Systems (MEMS) technology has emerged with low-power consumption, compact-size, constant quality, and high sensitivity. High stability is expected due to small size of a sensing unit, and individual difference of each sensors is believed to be small because of using the MEMS technology. Influence of movement of the sensor itself is small due to mechanism of pressure transmission. Nankai Trough seafloor network for earthquakes and tsunamis-net (N-net) will be equipped with the new sensors. Before routine observations using this new sensor, we evaluate performance of the new silicon resonant sensor for seafloor pressure observation.

An existing Free-fall pop-up type Ocean Bottom Pressure gauge (OBP) has a quartz resonant sensor. We replaced the sensor to the new silicon sensor, and performed seafloor observations off Boso peninsula near Tokyo. We obtained pressure data from two new sensors. Ambient noise spectra of the new sensor was compared to that of the ordinary sensor which was installed at the same position. The new and ordinary sensors have identical noise level at periods longer than about 50 s. However, the new silicon sensor seems to have higher noise levels at periods between 50 s and 10 s. The new sensor observed sea level fluctuation by volcanic eruption in Tonga and The identical waveforms were obtained from the new and ordinary sensors.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Reduced array detections at Gräfenberg stations caused by wind turbine noise

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The Gräfenberg array situated in the Frankonian Jura in Germany is the first digital broadband array on earth delivering continuous waveform data since almost 50 years. Besides its outstanding status in global seismology it is also National Technical Mean in the frame of the Comprehensive Test Ban Treaty since it recorded many nuclear explosions since the 1970ies from all known nuclear test areas. The high sensitivity of the array could be retained for many decades, only recently the detrimental influence of wind turbines (WT) in the area substantiated. Even though the individual stations since 2016 are protected by a WT tabu zone of 5 km radius around each location an increasing wind dependence of the array detections has been found. Comparisons of FK detection statistics of the year spans 2001-2007 (before WT installations) and 2015-2021 (after WT installations) show that about 13% of the detections are lost due to WT generated seismic noise, when averaging over all times. At high wind speeds the loss rate can be as high as 40%. This is caused by a few WTs installed inside the protection zone before 2016 and intensified by the large number of WT installations in distances larger than 5 km from the station locations. Due to the intended increase in wind power installations in Germany a further degradation of the array sensitivity can be expected.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

System Design of Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net) and its Long-Term Reliability

DOI: 10.57757/IUGG23-2211 - LINK

Tetsuya Takeda[1], Shin Aoi[1], Takashi Kunugi[1], Masanao Shinohara[1,2], Takayuki Miyoshi[1], Kenji Uehira[1], Masashi Mochizuki[1], Narumi Takahashi[1]
[1]National Research Institute for Earth Science and Disaster Resilience, Network Center for Earthquake Tsunami and Volcano, Tsukuba, Japan
[2]Earthquake Research Institute the University of Tokyo, Center for geopysical observation and instrumentation, Tokyo, Japan

N-net is now under construction in western half of the source area of the anticipated Nankai trough earthquake and 36 observatories will be deployed on the deep seafloor. The measurement device at each observatory digitizes the output voltage of seismometers with a sampling rate of 1 kHz by 24-bit A/D converter. The output data is transmitted to two landing stations and finally decimated to data with a sampling rate of 100 Hz and a dynamic range of 130 dB. The measurement device has a frequency counter which counts the number of cycles of square waves generated from the newly developed pressure gauge incorporating silicon resonator. The counted data is also transmitted and decimated to 10 Hz and converted to pressure data. The observed data is time-stamped with a precision of 1 μsec or better at each observatory using the precise time clock synchronized to the GNSS disciplined one and signal transmission delay information. The communication between the observatory and the landing station is peer-to-peer through the submarine optical cable and performs reception of STM-4 data compliant with SDH transmission technology. N-net communication system allows IP communication, implementing IP packets in SDH payload. The whole N-net system is designed for long life because it is not easy to repair troubled devices on the seafloor. To enhance reliability of the system, we adopted a variety of redundancies such as two subsystems of offshore and inshore, two landing stations, duplicated sensors, and so on, which enables to keep running over 20 years.

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S02 - Posters - International, National, Regional and Local Networks and Earthquake Data Centers: Highlights and Challenges

Earthquake monitoring in Northern Germany and adjacent seas

DOI: 10.57757/IUGG23-1978 - LINK

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[1]Christian-Albrechts-Universität zu Kiel, Insitute of Geosciences, Kiel, Germany
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[4]University Hamburg, Insitute of Geophysics, Hamburg, Germany

Northern Germany is a weak seismicity region with low level of exposure to seismic hazard. Accordingly, seismic hazard assessment has been pursued with low priority in the past. Rather poor observational conditions in the North German Basin are also a limiting factor for seismic monitoring. In a multi-institutional collaboration, we have been able to increase the number of permanent broadband stations in the North German Federal States of Schleswig-Holstein and Mecklenburg-Vorpommern from previously four in the year 2013 to currently fifteen. All data of the network are freely available through the EIDA node at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover.

Three complementary seismic arrays, notably on the islands of Heligoland in the North Sea and on Rügen in the Baltic Sea, improve monitoring capabilities of offshore areas. Data from these seismic arrays also provide an opportunity to investigate properties of oceanic microseism in epicontinental seas.

In addition to the development and operation of the seismic network, continuous event detection and analysis routines have been established at Kiel University. Besides low magnitude earthquakes, other natural phenomena like rockslides on cliffs or subrosion events have been repeatedly detected. Known controlled explosions provide an opportunity to quantify detection and location capabilities of the network. The recent destruction of the Nord Stream gas pipelines proved the importance of ongoing network expansion, and the need and reliability of routine seismic monitoring in this region.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Non-linear softening and relaxation in rocks and geomaterials: A laboratory perspective

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[3]GFZ Potsdam, Geomechanics and Scientific Drilling, Potsdam, Germany

In rocks and other consolidated geomaterials, dynamic excitation leads to a fast softening of the material, followed by a slower recovery process where the material recovers part of its initial stiffness as a logarithmic function of time. This requires us to exit the convenient framework of time-independent elastic properties, linear or not, and investigate non-classical, non-linear elastic behavior. These phenomena can be observed during seismic events in affected infrastructure as well as in the subsurface. Since the transient material changes are not restricted to elastic parameters but also affect hydraulic and electric parameters as well as material strength, as documented for instance by long lasting changes in landslide rates, it is of major interest to characterize the softening and recovery phases.

To further characterize this behavior in a controlled environment, we perform experiments on Bentheim sandstone in a Materials Testing System triaxial cell with pore pressure and confining pressure control. Our sample is subjected to various low-strain loading cycles in both dry and water-saturated conditions, while an active acoustic measurement setup allows us to perform Coda Wave Interferometry to continuously monitor the changes in modulus in the rock.

Our transducer array allows us to observe the dynamic softening as well as the recovery processes in the sample during repeated loading phases of various time lengths. Our observations indicate high spatial, frequency content and lapse-time sensitivity of the observed velocity changes, indicating a rich landscape of concurrent effects and physical phenomena affecting our sample during these simple experiments.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Shear wave velocity model from Rayleigh-Wave Dispersion analysis beneath the Higher Himalaya-India

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We present the surface wave dispersion results from the recorded data of 16 broadband seismic stations in the Higher Himalaya region. The Higher Himalayas is seismically very active due to the convergence of the Indian Plate and the Eurasian Plate along a basal decollement known as the Main Himalayan Thrust (MHT). A portion of the area is located in the Kashmir seismic gap, which lies between the Kangra earthquake of 1905 and the Kashmir earthquake of 2005. A surface wave dispersion analysis has been carried out in order to understand the seismotectonic structure beneath the research area. The fundamental mode Rayleigh wave Green's functions have been estimated for station pairs using cross-correlation of vertical component ambient noise data. The generated group velocity maps from 2 to 15s indicate the substantial variation in crustal structure and exhibit strong relationships with well-known geological and tectonic phenomena in the studied region. We found a low-velocity zone in the middle crust of the higher Himachal Himalayas portion between 12 and 15 km deep, which may be caused by the presence of a crustal ramp structure beneath 12 to 22 km of the Main Central Thrust (MCT). Likewise, a shear wave velocity model has been obtained by inverting surface wave dispersion measurements for the Kishtwar region.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Pn wave velocity and anisotropy underneath the central segment of the North-South Seismic Belt in China

DOI: 10.57757/IUGG23-1462 - LINK

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We present a Pn wave velocity and anisotropy model of the central segment of the North-South Seismic Belt in China, where there are numerous stable basins and active faults, making this segment attractive for extensive studies. The model was obtained by a tomographic analysis of 49973 Pn wave phase readings collected by the China Earthquake Networks Center and temporary stations in Yunnan and Sichuan. The tomographic velocity model shows that the average Pn wave velocity is 8.06 km/s; prominent high-velocity (high-V) anomalies are visible under the Sichuan Basin, the Zoige Basin and the Ordos block, which clearly outline their tectonic margins. A pronounced low-velocity (low-V) zone is observed from the Songpan-Ganzi block to the Chuan-Dian and Daliangshan blocks, suggesting the presence of hot material upwelling. The station delay data show a gradual variation from negative to positive values, possibly reflecting a crustal thickness variation from the southwest to the northeast of the study area. A correlation between the Pn wave anisotropy and the distribution of velocity anomalies is observed: anisotropy is relatively weaker in the high-V anomaly zones beneath stable basins, while it is stronger in the low-V anomaly zones and the high-to-low-V anomaly transition zones. The high-resolution velocity and anisotropy tomographic model that we obtained could also provide a better understanding of the study area seismicity, since the occurrence of strong earthquakes seems to be related to the presence and strength of lateral heterogeneities at the uppermost mantle level.

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Separation of source, attenuation and site parameters of 2 moderate earthquakes in France: an elastic radiative transfer approach

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[2]Observatoire Midi-Pyrénées, Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
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An accurate magnitude estimation is necessary to properly evaluate seismic hazard. Unfortunately, magnitudes of small earthquakes are subject to large uncertainties due to high-frequency propagation effects which are generally not properly considered. To address this issue, we developed a method to separate source, attenuation and site parameters from the elastic radiative transfer modeling of the full energy envelopes of seismograms. The key feature of our approach is the treatment of attenuation -both scattering and absorption- in a simple but realistic velocity model of the Earth's lithosphere, including a velocity discontinuity at the Moho.

Our separation method is based on a 2-steps inversion procedure. First, for each source-station pair, we retrieve optimal frequency-dependent attenuation parameters from the fitting of observed energy envelopes in the 0.375-24Hz band. In a second step, we correct for regional propagation effects to determine site amplification and source displacement spectra. From the latter, we estimate the moment magnitude Mw.

The inversion procedure is applied to the 2019 ML 5.2 Le Teil and 2014 ML 4.5 Lourdes earthquakes, which both occurred in Southern France. The inversion results confirm a significant variability in the attenuation parameters (scattering and intrinsic absorption) at regional scale and a strong frequency dependence. We determine moment magnitudes Mw 5.07±0.17 for the Le Teil earthquake and 4.13±0.13 for the Lourdes earthquake, in good agreement with previous estimates. In the future, we intend to automate our method and apply it routinely to smaller earthquakes for which traditional methods are not readily applicable due to the complexity of waveforms.

An accurate magnitude estimation is necessary to properly evaluate seismic hazard. Unfortunately, magnitudes of small earthquakes are subject to large uncertainties due to high-frequency propagation effects which are generally not properly considered. To address this issue, we developed a method to separate source, attenuation and site parameters from the elastic radiative transfer modeling of the full energy envelopes of seismograms. The key feature of our approach is the treatment of attenuation -both scattering and absorption- in a simple but realistic velocity model of the Earth's lithosphere, including a velocity discontinuity at the Moho.

Our separation method is based on a 2-steps inversion procedure. First, for each source-station pair, we retrieve optimal frequency-dependent attenuation parameters from the fitting of observed energy envelopes in the 0.375-24Hz band. In a second step, we correct for regional propagation effects to determine site amplification and source displacement spectra. From the latter, we estimate the moment magnitude Mw.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

3-D transdimensional inversion of surface wave dispersion and receiver functions

DOI: 10.57757/IUGG23-3657 - LINK

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Geophysical inverse problems (seismic tomography) are often significantly underdetermined meaning that a large range of parameter values can explain the observed data well within data uncertainties. Markov chain Monte Carlo (McMC) algorithms based on Voronoi cell parameterizations have been used for quantifying uncertainty in seismic tomography for a number of years. Since surface waves constrain absolute shear velocities and receiver functions (RFs) image discontinuities beneath receiver locations, joint inversion of both data types based on McMC become a popular method to reveal the structure near Earth's surface with uncertainty estimates.
A one-step 3-D direct inversion based on the reversible jump McMC and 3-D Voronoi tessellation is proposed by inverting for 3-D spatial structure directly from frequency-dependent traveltime measurements and RFs. We take into account the dipping interfaces according to the Voronoi parameterisation, meaning that back azimuth and incidence angle of individual RFs must be taken into account. We present synthetic tests demonstrating the method. Individual inversion of surface wave measurements and RFs show the limitation of inverting the two data sets separately as expected: surface waves are poor at constraining discontinuities while RFs are poor at constraining absolute velocities. The joint solution gives a better estimate of subsurface properties and associated uncertainties. Compared to conventional two-step inversion which may produce bias propagating between two steps and loses valuable lateral structure variations, the direct 3-D direct inversion not only produces more intuitively reasonable results but also provides more interpretable uncertainties.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Impact of reservoir loadings on seismic ambient noise in the Koyna-Warna region, western India

DOI: 10.57757/IUGG23-1623 - LINK

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To understand the power spectral variations of the ambient noise, we computed the power spectral density-probability density functions PSD-PDF of continuous seismic noise recordings from Koyna-Warna seismic zone, a well-known site for reservoir-triggered seismicity. The analysis helps us to know the impact of water level changes of the reservoirs on the amplitudes of ambient noise in the range 0.01 Hz to 5 Hz. Several studies have indicated a strong impact of reservoir loading on crustal stress and subsurface pore pressure. The comparison of annual ambient noise power levels within the band 0.01Hz to 3Hz with the new global noise models suggests significant deviations on an average. We have noticed cyclic changes and modulation of power and probability at primary and secondary microseism bands from the monthly PSD-PDF variations for the year 2015. Our results indicate high noise levels at the secondary micro-seismic level (~5Sec) to the north of the seismicity zone, which is close to the Koyna Dam, compared to all other directions. An increase in the randomness over frequencies 0.01Hz to 3Hz was observed just before the monsoon i.e. during the month of June, evidenced by reduced power spectral probabilities. The results also indicate a reduction in the noise power during the post-monsoon season, which may be associated with increased loading of the Koyna reservoir. The results suggest the modulation of noise levels by the changing reservoir water levels, particularly during pre and post-monsoon seasons in the Koyna-Warna region.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Head-wave correlations from ambient noise in a shallow ocean waveguide with a layered seabed

DOI: 10.57757/IUGG23-1392 - LINK

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[5]University of Victoria, Ocean Networks Canada, British Columbia, Canada

In this study, we derive the travel times and angles of arrival of head-wave correlations from ocean ambient noise in a shallow ocean waveguide with a layered seabed using a vertical line array. The up- and down-going head waves from the same sediment interface are correlated, and their travel time differences give the travel times of head-wave correlations. The angles of arrival of head-wave correlations from different interfaces depend on the sound speeds in the water and seabed layers according to Snell's law. The head-wave correlations from the water-sediment interface are periodic in time, while those from deeper interfaces show a more complicated time arrival structure. Combining the travel times and angles of arrival of head-wave correlations from different interfaces, it is able to invert for all the sound speeds and layer thicknesses in the water and seabed. The simulation with wind noise and a sediment layer over a half-space seabed verifies the inversion performance.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Near-surface shear-wave velocity structure of a fault zone in southwestern Taiwan using a dense seismometer array

DOI: 10.57757/IUGG23-2556 - LINK

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In southwestern Taiwan, several active faults ever induced massive earthquakes are distributed at the Western Foothill. The seismicity is quite high and widespread in this region. A dense short-period seismometer array with ninety-six stations was temporarily set in the fault zone between November 2020 and January 2021 to collect continuous ground motion data for evaluating the seismogenic characteristics and seismic hazard. This study applied the high-frequency receiver function method to estimate one-dimension shear-wave velocity profiles beneath these stations. The earthquake records of the array were collected and analyzed with appropriate parameters and procedures. Furthermore, the site responses of these stations were also evaluated using the horizontal-to-vertical spectral ratio method. The site effect and shear-wave velocity variation of the fault zone were constructed to discuss the near-surface complex structure in the region.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Joint active and passive MASW for landslide site investigation: A case study from Northwest Taiwan

DOI: 10.57757/IUGG23-1169 - LINK

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Multichannel analysis of surface waves (MASW) is a seismic method used for engineering and environmental exploration. Passive MASW is becoming more popular due to its advantages, such as compensating for the lack of low-frequency information in active MASW. Therefore, more information of the subsurface can be obtained by using the two methods jointly.

To test the performance of the passive MASW in landslide investigation, a 131-meter seismic array was deployed along a slope close to a railway. Seismic waves produced by the active source and ambient noise were acquired. Analyzing the ambient noise data showed that a stable dispersion curve can be obtained within a few minutes. The dispersion curves of every common source gather showed the phase velocities of the active and passive methods at the overlap frequency range are similar which shows these two methods are consistent. Thus, all dispersion curves were jointed and collected to inverse the S-wave velocity.

The inversion results showed a 2-D subsurface structure down to 60 meters, which is more than the double depth using only active methods (25m). The weak material (soft clay) was identified at a depth of 11-18 meters, and soft to dense sand was observed at 18-34 meters. The base rock is identified at the depth blow 34 m with an S-wave velocity exceeding 750 m/s. Study result demonstrates the efficiency of using both active and passive surface waves to investigate landslides on a slope and suggests reliable results can be obtained from short-time ambient noise nearby a railway.

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Estimation of high-frequency source radiation energy of small earthquakes in Japan using seismogram envelopes considering the heterogeneous seismic structure

DOI: 10.57757/IUGG23-0642 - LINK

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Recent progress in the theory of seismic wave scattering has shown that the excitation of coda waves depends on hypocentral depth, and analyses of coda waves recorded by dense seismic networks have revealed heterogeneous excitation of coda waves. These facts should be considered when we analyze coda waves further. In this study, we estimate source radiation energy from full seismogram envelopes considering heterogeneous seismic structures.

First, we calculate synthetic envelopes using the Monte Carlo simulation based on the radiative transfer theory and the Born scattering coefficients with a 3-D velocity structure. We conduct a grid search to find appropriate parameters of intrinsic and scattering attenuation that reproduce the shape of each observed envelope, then we calculate source and site terms by an envelope fitting method.

We applied the method to small earthquakes that occurred around central Japan. The range of magnitude was 3.0 to 4.5, and the depth was down to 100 km. We estimated source radiation energy at the frequency ranges of 1-2 and 2-4 Hz. The estimated source radiation energy correlated with magnitude in both frequency ranges. In addition, we found that deep earthquakes tended to have larger energy than shallow ones. This result may reflect the depth dependency of the physical properties of the earth.

Acknowledgments

We used the seismic records of the Hi-net (doi: 10.17598/NIED.0003). This work was partly supported by the JSPS KAKENHI Grant Nos. JP18K13622 and JP21K14002.

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S03 - Posters - Seismic Scattering and Absorption, Ambient Noise, and Monitoring Earth's Structure

Seismic tomography and attenuation models for the geophysical characterization of the Krafla volcanic area

DOI: 10.57757/IUGG23-2177 - LINK

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The characterization of underground structures is crucial for explorative studies in geothermal systems. As recently demonstrated, analysis of the propagation of seismic waves provides information on physical rocks' behavior and alternative assessments of the brittle-ductile transition (BDT) depth [1]. In particular, the decay of the amplitude of the seismic waves (i.e. seismic attenuation), which is usually described by a "quality factor" Q, depending on the seismic scale, could be used as an indicator of the subsurface heterogeneities.

In this study, we investigate the sensitivity of the seismic velocity and attenuation to the crustal heterogeneities, by implementing a Q seismic tomography of the Krafla volcanic system, an area affected by young tectonics and hot thermal conditions. The applied method solves for Qp perturbations, using a combination of a spectral decay technique to retrieve the attenuation operator (t*) and tomographic inversion [2]. The distribution of seismic wave velocities is obtained from a 3D tomographic inversion, using 1453 earthquakes detected from a local seismic network (2009-2012) [2,3].

The obtained Qp variations up to a depth of 4 km are interpreted together with the seismic wave velocity values [3]. The joint interpretation helps discriminate between anomalies related to temperatures and compositional heterogeneities, defining the main structures of the area. We also try to define the BDT depth, based on the strong reduction of the Qp, related to hot temperatures/melt conditions.

References

[1] Natale Castillo et al., 2022. https://doi.org/10.1016/j.gloplacha.2022.103978.

[2] Lanza et al., 2020. https://doi.org/10.1016/j.jvolgeores.2020.106804

[3] Schuler et al., 2015. https://doi:10.1002/2015JB012350

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Groundwater level measurement using the ambient seismic time series across the Santa Ana Basin

DOI: 10.57757/IUGG23-4860 - LINK

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Groundwater withdrawal for domestic, industrial, and agricultural consumption has intensified in Santa Ana Basin, California. It's imperative to monitor the hydraulic head for groundwater management and the sustainability of water resources. Observation wells provide direct information on groundwater level. However, the sparse spatial coverage makes it inappropriate for large-area studies. Satellite-based remote sensing observations, such as the GRACE/FO data, can obtain regional groundwater storage. Nevertheless, it has coarse spatiotemporal resolution and suffers non-uniqueness between water volume and aquifer depths. Recently, the seismic velocity change (dv/v) calculated by the cross-correlation of ambient seismic time series has been adopted to reveal the groundwater level change. The dv/v has the advantage of illustrating the purely elastic response of the aquifer. Here, we measure the dv/v change at eleven seismic stations from 2000 to 2022 to study the spatiotemporal variabilities of groundwater levels in the Santa Ana basin. Our results manifest good consistency with observed groundwater levels with a correlation coefficient reaching up to 0.8, which means dv/v can reveal both long-term and seasonal fluctuations. Furtherly, the dv/v showed great agreement with precipitation data, which means the groundwater levels in the Santa Ana basin are modulated mostly by the rainfall pattern. As an independent measurement, dv/v shows great promise for regional groundwater study.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

CFM: a convolutional network for first motion polarity classification of earthquake waveforms

DOI: 10.57757/IUGG23-3553 - LINK

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The knowledge of the crustal stress field is crucial for understanding the seismic activity in an area that, in turn, requires an in-depth knowledge on the dynamics of the crust. To that end, the reconstruction of focal mechanisms of earthquakes as reliable as possible is a preliminary and basic requirement to infer proper source mechanisms. Currently, the fault plane solution method, using P-wave polarities, is still frequently used. Anyway, manually determining the polarities of P-waves is time-consuming and susceptible to human error. These issues can be solved by automated processes thorough the application of machine learning techniques.

In our study, the Convolutional First Motion (CFM) network, a Deep Convolutional Neural Network, is presented. It is utilized to categorize seismic traces based on the polarity of the P-waves' first motions. We used waveforms from two datasets: the Italian seismic catalogue INSTANCE and waveforms from earthquakes that occurred in the Mount Pollino region of Italy between 2010 and 2014.

We developed a method based on Principal Component Analysis and Self-Organising Maps, which enabled a clustering process to identify sets of appropriate traces. The network was trained using 130˙000 time windows centered on P-wave arrival times relative to waveforms in the INSTANCE catalogue

The network achieved accuracies of 95.7% and 98.9% on two test sets that were generated using the datasets for Mt. Pollino and a portion of the INSTANCE catalogue, respectively.

This work has been partially supported by PRIN-2017 MATISSE project, No 20177EPPN2, funded by Italian Ministry of Education and Research.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Automatic recalculation of the local magnitudes (ML) for seismic events in Romania: validation through multiple case-study analyses

DOI: 10.57757/IUGG23-2835 - LINK

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In a seismically active region like Romania, an accurate and homogeneous determination of the seismic events' magnitude is important for properly characterising events' size and defining seismogenic areas. We present an automatic and reproducible scheme for local magnitude (ML) calculation based on the reviewed bulletins of the updated Romanian earthquakes catalogue (ROMPLUS) and the associated horizontal components of the station recordings. The applicability of the method is evaluated on three different case-studies, considered as typical examples, using earthquakes recorded between 2014 and 2023. Firstly, the magnitude calculation scheme is applied to anthropogenic and natural seismic events recorded in the North Romania regions, known for the quarries' exploitations. Secondly, we analyse earthquakes from the Vrancea seismic region, mainly the events that occurred during the February 2023 Turkey-Syria damaging earthquake sequence, in order to review the magnitudes of the local events whose waveforms overlap with the surface waves generated by this sequence. Finally, the intense earthquake sequence from the Central Southern Carpathians seismic zone, with the main shocks corresponding to doublet earthquakes with magnitudes (ML) 5.2 and 5.7 and over 800 aftershocks, was analysed to evaluate the stability of the scheme.

We show that the proposed approach is able to provide a reliable automatic estimation of ML for seismic events, by minimising the magnitude error and allowing to select recordings with good signal-to-noise ratios. Our results demonstrate the usefulness of this scheme for the homogenisation of the ROMPLUS catalogue and its future extension to other seismically active areas of Romania.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Improving aftershock decision criteria for the 2016 Gyeongju and 2017 Pohang earthquakes in South Korea

DOI: 10.57757/IUGG23-0650 - LINK

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During the last six years, South Korea has experienced two of its largest earthquakes since instrumental recording began. A specific set of aftershock criteria is necessary for earthquakes that occur near the mainshock. Despite the discovery of the fault associated with the mainshock, some aftershocks have a low relevance to the fault where the mainshock occurred. Providing detailed information about aftershocks to people living near fault areas is important, and the difficulty in specifying their end time has prompted the need for improved criteria. We propose improved criteria for determining the aftershocks of the ML5.8 Gyeongju and ML5.4 Pohang earthquakes.
The criteria are divided into temporal and spatial components. The earthquake Mw-fault information relationship of Wells & Coppersmith (1994) is used for the spatial criterion to calculate the extent of ruptures that can occur based on magnitude. The rupture range is conservatively applied to the Mw5.6 Gyeongju and Mw5.4 Pohang earthquakes. The spatial aftershock distribution is defined within 4 km of the earthquake fault line associated with the mainshock, and it is based on the empirical relationship of the fault down-dip rupture width and the earthquake moment magnitude of past earthquakes. For the temporal criterion, the endpoint of aftershocks is defined as the time when the number of earthquakes per unit of time after the mainshock is equal to or less than the average seismicity in the five years before the mainshock. Using these criteria, the study concludes that the aftershock sequences of the Gyeongju and Pohang earthquakes are still ongoing.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

From analog to digital instrumentation and the importance of expanding the seismic network - Targu-Jiu seismic sequence study case

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The Targu-Jiu seismic zone of Romania is well known for the crustal events with moderate magnitude (ML <5) that rarely occurred. The largest event, with an estimated local magnitude of 5.2 and depth of 9.9 km, was recorded in 1943. At that time, seismic monitoring was done with analog instruments and macroseismic observations.

At the beginning of 2023, a seismic sequence with main shocks as doublet earthquakes occurred on February 13th and 14th, with local magnitudes of 5.2, respectively 5.7, followed by over 900 aftershocks.

When the sequence started, the Targu-Jiu area was monitored by 45 seismic stations of the Romanian Seismic Network (RSN). Therefore, the earthquake parameters were determined accurately.

Moreover, for lowering the event magnitude threshold and a better seismic coverage, four more seismic stations were installed in the epicenter area, after the 5.7ML event recorded on February 14th.

The main goal of this paper is to highlight the importance of well-distributed seismic stations in the epicenter area and high quality recorded data. To reach the purposes of this study, two different approaches were conducted. Firstly, we used only the stations nearby the epicenter area. Then, we use data recorded by all the RSN stations (over 160 recordings for the 5.7 ML event). The results of this study showed that a better location is obtained when using stations well distributed in the epicentral area.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

HEX 2.0: an improved local seismic phase associator

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The task of association of seismic phases into events is particularly challenging in every workflow dealing with seismically active regions where dense networks are usually deployed. Additionally, recents developments of picking algorithms based on deep learning frameworks provide an increased number of phase onsets with respect to standard approach based on the computation of characteristic functions of the seismic waveforms. Especially the number of S-picks has been increased by orders of magnitude, which now requires the simultaneous association of P- and S-wave arrivals or even detecting events only based on S-wave arrivals. We present an improved version of HEX (Hyperbolic Event eXtractor), a new technique based on the logic of Random Sample Consensus here applied to association of seismic phases. Since this algorithm is particularly effective in dealing with high noise in the input data, we show the benefits of HEX2.0 to analyze picks from deep learning methods. These datasets are characterized by either detections of small amplitude earthquakes that, according to network geometry, may not show at a sufficient number of seismic stations to declare an event or, sometimes, to a high rate of false positives. The application of HEX2.0 on real data from a seismic sequence of Sannio-Matese (Southern Apennines, Italy) occurred in 2013-2014 show that: i) resulting events show a high number of phases compared to previous catalogs; ii) few phases are discarded in the event location. HEX2.0 provides an accurate, easy-to-use and computationally effective solution to the seismic phase association problem.

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Effect on a deep-learning, seismic arrival-time picker of domain-knowledge based preprocessing of input waveforms

DOI: 10.57757/IUGG23-4352 - LINK

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Automated procedures for seismic arrival-time picking on large and real-time seismological waveform datasets are critical for many seismological tasks. Recent, high-performance, automated arrival-time pickers mainly use deep-neural-networks applied to nearly raw, seismogram waveforms as input data. However, there is a long history in earthquake seismology of rule-based, automated arrival detection and picking algorithms that efficiently exploit variations in amplitude, frequency and polarization of seismogram waveforms.

Here we use this classical, seismological domain-knowledge to transform raw seismogram waveforms into input features for a deep-learning picker. We preprocess 3-component, broadband seismograms into 3-component characteristic functions of a multi-band picker (FilterPicker), plus the instantaneous modulus and inclination of the waveforms. We use these five time-series as input instead of the 3-component, raw seismograms to extend the deep-neural-network picker PhaseNet within the SeisBench platform. We compare the original, purely data-driven PhaseNet and our extended, domain-knowledge PhaseNet (DKPN), using identical training and validation datasets, with application to in- and cross-domain testing datasets.

We find that the explicit information targeting arrival-time detection and picking introduced by the domain-knowledge processing enables DKPN to be trained with smaller datasets than PhaseNet. Relative to PhaseNet, DKPN shows improved performance and stability for P picking and slightly improved S picking, especially for cross-domain application. With increasing training dataset size PhaseNet performance generally improves and converges to that of DKPN, except for cross-domain P picking. The results suggest that DKPN primarily needs to learn pick characterization, while PhaseNet additionally requires learning the more difficult task of arrival detection.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Enhancing Earthquake Detection through Machine Learning: An Application to the 2017 Mw 8.2 Tehuantepec Earthquake in Mexico

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Detecting and monitoring earthquakes remains a persistent challenge in seismology. The ever-increasing volume of seismic data provides us with a great opportunity to develop more robust phase picking and association methods. While the application of machine learning models for earthquake monitoring has gained significant attention, there remains a gap in validating the efficacy of these models for unseen data. This study reviews a practical workflow that leverages machine learning techniques for phase picking and association following the September 8th, 2017, Tehuantepec earthquake (M8.2). The September 8th earthquake ranks among one of the strongest intraplate events recorded in the history of México, causing significant damage and deaths in the states of Oaxaca, Chiapas, Tabasco, and México City. The Servicio Sismólogico Nacional (SSN) alone has located over 30,000 aftershocks in six months following the mainshock. The volume of seismic recordings gathered from permanent and temporary networks deployed from collaborations of the University of Texas at El Paso, Universidad Autónoma Cuidad Jaurez, and SSN and the tectonic complexity of this rupture have made it strenuous to use traditional automated detection methods. Using *PhaseNet*, a convolutional neural network developed for picking arrival times of P and S waves, and the Gaussian Mixture Model Association, *GaMMA*, an unsupervised association method based on a Bayesian Gaussian Mixture Model, we aim to review a practical workflow for earthquake detection and a catalog of relative earthquake locations for this large number of aftershocks, contributing to studying the broader geotectonic setting of the Tehuantepec region.

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a catalog of relative earthquake locations for this large number of aftershocks, contributing to studying the broader geotectonic setting of the Tehuantepec region.

S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Modeling the structure of the Água Bonita basin, Brazil, from the inversions of horizontal to vertical spectral ratio (HVSR) peaks

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The advance in seismic acquisition requires more techniques compatible with urban means and environmentally friendly. A**ccordingly**, the horizontal-to-vertical spectral ratio (HVSR), is a method that is becoming much more popular and convenient. Used with a lot more frequency to help estimate structures and draw a better model for shallow structures. Following the tested and approved procedures described in the SESAME Project, we acquired 58 measurements in 6 profiles, including fixed and temporary stations. The study site is a strike-slip basin, called Água Bonita, located in the state boundaries of Tocantins with Goiás, in the center-North of Brazil. The deep structure of this basin is well-constrained based on geological and geophysical data. Therefore, we could compare the reliability of our depth estimates. Following the previous acquisitions, we used broadband and short-period seismometers for the acquisition, positioning the profile's location transversal to the basin length. Due to the basin geometry, we searched for a correlation between the HVSR frequency results and the sedimentary thickness, type of sediment, and overall location within the geological context. The inversion of the HVSR frequency peaks was used to estimate the depth of the layers observed. The preliminary results indicate an association between sedimentary thickness and lithology contrast. It obtained frequencies ranging from 0.2Hz at the edges to 11Hz in the basin's center. With the data acquired, we were able to trace a 3d model of the basin and possibly better identify other faults within the basin changing its geometry alongside its length.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Waveform based cluster analysis of seismicity in the Eastern Alps

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The Swath-D network was a temporal seismic array in the Eastern Alps, as part of the AlpArray project. The array consisted of 154 broadband stations and was active from late 2017 to late 2019. Using data from this network, we constructed a comprehensive local seismicity catalogue based on template matching. We developed a workflow to derive picks for these low magnitude events that typically have low signal to noise ratios. This allowed us to relocate part of the detected seismicity with high resolution, exploiting the densified station distribution in the area.

Based on this enhanced earthquake catalogue for the Eastern Alps, we identified multiple clusters with high seismicity rates. We perform an iterative template matching scheme to increase the number of detected events, and apply a relative relocalisation to further increase the spatial resolution. Graph theory was applied to visualise event interconnectivity based on waveform similarity between the clustered events. This allows us to derive network features, which we compare to the spatiotemporal characteristics of each of the clusters, as well as source properties of the clustered events.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Application of phase identification using deep learning-based technology for local earthquakes in the Southern Korean peninsula

DOI: 10.57757/IUGG23-2137 - LINK

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In order to identify the phase of seismic waves, deep learning-based phase identification technologies have recently been developed.It is known that deep learning-based phase identification technology can accurately determine the arrival time of the phase and also identify S waves, which are relatively more difficult to detect than P waves. Approximately 2.4 million seismic data from STEAD and INSTANCE were used to develop deep learning-based phase identification techniques (Sheen, 2021).In this study, a deep learning-based phase identification technology was applied to 871 earthquakes with a magnitude of 2.0 or higher on the Korean Peninsula and compared to the manual seismic wave identification results provided by the Korea Meteorological Administration. As a result, it was confirmed that most of the P-waves of the seismic wave could be identified successfully, and the S-waves were also identified. In addition, the optimal criteria for determining the phase status of P and S-waves were established using deep learning-based seismic wave identification technology. To this end, the learning model predicted the probabilities of P&S-waves, and noise from the three-component seismic waveform, and judged the section where the probabilities of P&S-waves exceeded a specific threshold to be a phase. It was confirmed that the performance of the artificial intelligence model changed according to this specific threshold, and the optimal threshold yielding the highest performance of the AI model was selected. As a result, it was confirmed that as the threshold value increased, the model accuracy increased while the reproduction rate decreased.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Seismic Ambient Noise Interferometry along Optical Fibers: What Insights can Distributed Acoustic Sensing provide?

DOI: 10.57757/IUGG23-4434 - LINK

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We explore the ambient noise wave field recorded on different optical fibers interrogated during distributed acoustic sensing (DAS) campaigns in Iceland and Germany. DAS is a relatively new technology that allows for measurements of acoustic strain signals at densely spaced observation points along buried optical fibers. Ambient noise interferometry, in particular single-channel auto-correlation, is potentially a powerful technique for resolving the structure of the subsurface medium and characterizing its properties below a seismic sensor. Combining these two techniques to extract the ambient noise auto-correlation functions from horizontal strain rates all along the densely spaced locations on the fiber we obtain coherent signals that correlate over multiple observation points. We are challenged by the separation of the super-positioned non-stationary ambient noise field and the seismic response of the subsurface. We test our processing workflow and results against independent methods. (1) A controlled vibro-seis experiment and (2) seismic ambient noise analysis of a large-N three-component seismic nodal array which was co-located with the optical fiber in Iceland.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Automatic unsupervised classification of tectonic tremor signals in continuous seismic records

DOI: 10.57757/IUGG23-4852 - LINK

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Continuous seismic records include various earthquake signals such as ordinary fast earthquakes and slow earthquakes like tectonic tremors. A machine-learning-based automatic classification approach would allow us to process a large amount of waveform data and to understand geophysical phenomena around a target seismic network. In this study, we propose an automatic unsupervised classification algorithm for continuous records based on frequency characteristics.
Our proposed algorithm first extracts frequency features by calculating running spectra, and then the vector quantization is performed in the feature space. After that, the data points are converted by the kernel principal component analysis and are clustered by the Ward hierarchical clustering algorithm in the mapped space. Finally, classification results are obtained by cutting the dendrogram at 1/4 of the maximum height.
We tested the proposed algorithm by applying to one-week-long continuous waveforms recorded at five temporary ocean-bottom seismometers to observe aftershocks of the 2004 M7.4 off the Kii Peninsula earthquake (Yamazaki et al., 2008). For every station, tectonic tremors with large amplitudes were assigned for unique class(es) different from those for background noises and fast earthquakes, indicating that the proposed algorithm successfully detected tectonic tremors with a good S/N ratio. We also compared the classification results to a tremor catalog compiled by manual inspection and found that the detection rate was 87%, which suggested that the proposed algorithm could detect tremors with a high detection rate although the algorithm did not use specific knowledge of tectonic tremor such as template.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Acoustic Emission event onsets recognized by Neural Network formalism

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One of the contemporary trend in seismology is process huge data sets automatically with use of Neural Network (NN) formalism. We present seismogram onsets interpretation obtained both by Convolution NN as well as Recurrent NN approach. We investigated data from Acoustic Emission loading experiment with Westerly Granite. Such data appeared to be suitable for testing of NN approach as they are more homogeneous then data originated from natural earthquakes, but simultaneously they are complex enough not to be of trivial interpretation. We designed NN architecture, learned in and compare the results with biased interpretation. We were searching not only for onsets on individual seismograms but we try to identified the whole events. In addition to automatic onsets identification we (also automatically) determined event location and seismic moment tensor. Comparison with biased data proved that these automatically obtained values can be successfully used as preliminary estimation at least. Problems of multiple events identification are discussed as well. The method has a potential to be applicable on natural earthquake seismograms.

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Analysis of the 2020-2021 earthquake swarm in the Eastern gulf of Corinth using high-resolution template matching catalogs

DOI: 10.57757/IUGG23-4417 - LINK

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[2]Hellenic Mediterranean University Research Center, Institute of Physics of Earth's Interior and Geohazards- UNESCO Chair on Solid Earth Physics and Geohazards Risk Reduction, Heraklion, Greece

An earthquake swarm occurred during 2020-2021 at the Perachora peninsula, in the eastern Gulf of Corinth (Greece), one of the most seismically active areas in Europe. In this work, we analyzed the swarm using a high-resolution earthquake catalog and advanced processing techniques. We employed both single-station and multi-channel template matching to produce additional detections of over 7,600 and 24,000 events, respectively. The resulting catalogs have different completeness magnitudes and location uncertainties for the added events. The frequency-magnitude distributions were characterized using the Gutenberg-Richter scaling relation, examining possible b-value temporal variations. We found that the seismic bursts associated with the swarm were short-lived and dominated the catalogs. Spatiotemporal clustering methods were used to analyse the swarm's evolution, showing that the seismicity rate significantly increased, likely due to a pore-pressure transient, without stress transfer caused by a major earthquake. Migration velocities, high b-values and clustering effects of multiplet families, observed at all time scales, suggest a pore-pressure triggering mechanism. Some anomalies in the frequency-magnitude distribution of the enhanced catalogs were observed, mainly attributed to the poor network coverage of the area of interest. Despite these limitations, the enhanced catalogs can be quite useful in studying the spatiotemporal properties of microseismicity in the region. This study highlights the importance of high-resolution data and advanced analytical techniques in understanding earthquake swarms in tectonically active regions.

Acknowledgements

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 00256).

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Evidences of continuous tremor-like source processes in W-Bohemia and Vogtland before the earthquake swarm in April 2021

DOI: 10.57757/IUGG23-2399 - LINK

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The ICDP project "Drilling the Eger Rift" focuses on geodynamic processes in W-Bohemia and Vogtland, such as earthquakes and subsurface fluid flows. Therefore, three boreholes have been drilled and will be instrumented with 3D seismic arrays. The pilot 3D array has 10 borehole geophones with a 10 Hz corner frequency and is surrounded by a surface array with 12 4.5 Hz geophones. The data is recorded by Earth Data Loggers with a sampling rate of 1000 Hz.

The goal is to locate seismic noise sources up to a distance of 15 km that may be linked to fluid migration in W-Bohemia. We analyze continuous seismic noise records of more than 20 stations from regional networks and our seismic array. Differential PSDs were calculated in different frequency ranges to find continuous tremor-like seismic sources before the earthquake swarm in April 2021. Our next step is to locate these sources using regional networks and the 3D seismic array.

The analysis revealed an increase in seismic noise between 4-8 Hz for a 2-hour period on April 5th, 2021, one day before the earthquake swarm started. Seven stations in the region show a median differential PSD level at least three times higher than the differential PSD level for the entire day. These stations are located up to a distance of 12 km to the Nový Kostel focal zone, where most of the earthquakes occurred. The increase is also compared to Radon concentrations measured at Hartoušov (W-Bohemia) to find possible coincidence.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Supervision of velocity models used in Reykjanes Peninsula, SW of Iceland

DOI: 10.57757/IUGG23-0564 - LINK

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Processing of seismological data requires knowledge of appropriate velocity model. Due to ongoing investigations of prominent geological regions usually numerous velocity models by different authors have been developed there. The question which arises is which one to use. This is also the case for Reykjanes Peninsula (RP) in SW Iceland, where the REYKJANET seismic network was built to monitor local seismicity. At present, five velocity models come into consideration in RP (four 1D gradient models and, one 3D tomographic model).

We have tested all the five models by common methodology. It includes discussion of results of (i) hypocenter localization, (ii) P-wave polarization at station positions and, (iii) Rayleigh-wave dispersion. Alternatively, 1D velocity models have been combined with stations corrections thus yielding efficiently pseudo-3D models.

All the tested models provide hypocenters whose traveltime residuals can be classified into two groups ((i) 1D models without station corrections and (ii) 3D tomographic model and 1D models with station corrections). Hypocenter coordinates differ slightly according the used model. Bigger differences between the models are due to the predicted P-wave polarization and Rayleigh-wave dispersion. This issue is connected with bigger sensitivity of those parameters to the surface properties of the models.

Our proposition is to select the best one 1D velocity model supplemented with station corrections and use it anywhere possible. Using of a more complex 3D model would be usually not highly beneficial. 3D tomographic model is, however, one of not-so-many tools how to discover geological features of the underground.

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Earthquake detection and hypocenter relocation in Central Pyrenees: the case of l'Alt Urgell-Andorra seismic sequence (2021-2022).

DOI: 10.57757/IUGG23-3108 - LINK

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Deparment of Geodynamics- Stratigraphy and Paleontology, Madrid, Spain
[2]Andorra Recerca+Innovació, Andorra Recerca+Innovació, Sant Julià de Lòria, Andorra
[3]Spanish National Research Council, Geosciences Barcelona GEO3BCN - CSIC, Barcelona, Spain
[4]University of Oklahoma, Oklahoma Geological Survey, Norman OK, USA

On 2022-02-01, the mainshock of a seismic sequence that started in 2021 struck between l'Alt Urgell (Catalonia) and Andorra la Vella (Andorra) in the Central Pyrenees area. This magnitude (Mw) 4.0 earthquake, which alerted the population of the vicinities, was followed by low-magnitude aftershocks. In this work, we aim to obtain a new catalog through machine-learning procedures. We used the easyQuake python package, which allowed us to build new catalogs after detecting earthquake arrival times within seismograms recorded by several stations in the study area. Using different pickers, we obtain those machine-learning catalogs and compare them against data from regional agencies. We observed that, depending on the deep-learning model, the new catalog matched a high percentage of the original dataset recorded by the agencies. Besides that, we noted that some earthquakes passed undetected by the routine processing of these agencies. Then, using the new arrival times, we relocated the hypocenters using a 1D velocity model of the area following a non-linear location inversion approach. Our results show low uncertainties, which suggest that the arrival times detected by the machine-learning software are accurate enough to obtain constrained hypocenters. We conclude that this procedure could be advantageous for agencies and organizations that run a regional network in addition to the standard routine procedure carried out by expert scientists and technicians.

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Implementation of an array and a rotational sensor on Piton de la Fournaise volcano, La Réunion

DOI: 10.57757/IUGG23-4075 - [LINK]

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[2]Université de Paris- Institut de physique du globe de Paris, Observatoire volcanologique du Piton de la Fournaise, La Plaine des Câfres, Réunion
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La Réunion, an island in the Indian Ocean, hosts the shield volcano Piton de la Fournaise that recently tends to erupt up to twice per year. The seismic recordings show a great signal diversity including tectonic and volcano-tectonic (VT) earthquakes, eruption tremor, (very) long period events along with a variety of rockfalls.

With the aim of testing the rotational sensor performance in comparison with a conventional seismic array, one rotational sensor and an array of seven seismometers were installed within the Enclos-Fouqué caldera. A permanent station of the monitoring network of the Observatoire Volcanologique du Piton de la Fournaise (OVPF) is included in the temporal network. Recordings of (volcano-) seismic signals, detected by the OVPF's network, are compared to those of the rotational sensor and the array.

We calculate the signal-to-noise ratio (SNR), derive the rotation rate using three array stations for array derived rotation (ADR) and compare the backazimuth (BAZ) results using different approaches. The rotational sensor and the array BAZ are furthermore compared to the OVPF's localizations.

Whereas the array BAZ for summit VT events and the rockfall agree with the locations of the OVPF network, the rotational sensor BAZ indicates possible agreement for the rockfall event. Further BAZ results from the rotational sensor are interpreted to be affected by site inhomogeneity. The array stations show higher SNR results than the rotational sensor. As burying of the instruments on site was not possible, the sensors are affected by wind, increasing the noise floor and decreasing the instruments' sensitivity.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Seismic structure of the crust and uppermost mantle beneath the Canary Islands using local earthquake tomography

DOI: 10.57757/IUGG23-3785 - LINK

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[2]*Instituto Geográfico Nacional, Centro Geofísico de Canarias, Santa Cruz De Tenerife, Spain*
[3]*Instituto Geográfico Nacional, Observatorio Geofísico Central, Madrid, Spain*
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Historically, the study of the seismic structure beneath the Canary Islands using local earthquakes has been hampered by the sparse distribution of recording stations and by the moderate seismic activity. Recently, the number of permanent stations from monitoring networks has significantly increased, from barely one seismometer per island in the early 2000s to more than 10 stations in each the most seismically active ones. Similarly, temporary deployments of broadband stations have also taken place in most of the islands, further increasing the station density. On the other side, the number of recorded earthquakes has also greatly increased. This is due in part to the seismicity associated with the 2011-2012 El Hierro and 2021 La Palma eruptions, but also because of the improvements in the detection capabilities of the monitoring network.

Here we present new P and S wave velocity regional models of the Canary archipelago and higher resolution models for the islands of Tenerife, La Palma and El Hierro. The bulk of the arrival time data used to obtain these models comes from the Instituto Geográfico Nacional (IGN) permanent monitoring network. We have augmented this dataset by incorporating arrival time data from recent temporary deployments, obtained using Deep Learning phase pickers. Because of the increased coverage of this new dataset, we are able to image features such as crustal thickness variations, magmatic intrusions, and regions of shallow (crustal) and deep (uppermost mantle) magma storage.

Funding has been provided by Spanish Ministry of Science and Innovation projects PID2020-114682RB-C31 and PID2020-114682RB-C32.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Analysis of the 2016 Central Italy earthquake sequence by using a refined earthquake catalog

DOI: 10.57757/IUGG23-0985 - LINK

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The 2016 Central Italy seismic sequence occurred within an area dominated by normal-fault systems present along the Apennines. The sequence began with the Mw 6.0 Amatrice event on the 24 August 2016, followed by the Mw 5.9 Visso event on the 26 October 2016 and then, two days later, the Mw 6.5 Norcia event. In this study, we aim at modeling the seismicity of this complex earthquake sequence in order to determine the location of highly-pressurized fluids under the studied area through swarms occurring during the sequence. To do so, we take advantage of a high-resolution earthquake catalog based on arrival times derived using a deep-neural-network-based picker. As a first step, we apply a density-based clustering algorithm (DBSCAN) to group earthquakes into dense clusters. The majority of the resulting clusters highlight distinct fault planes which indicates an activation of a complex fault network. We further define a 4-dimensional seismicity model based on the « Epidemic-Type-Aftershock-Sequence » (ETAS) model, that we modified to include an earthquake detection probability, as required by the continuous change of completeness magnitude. This allow us to compute the seismicity rate of the DBSCAN clusters. Swarms are then deduced based on the ratio between observed and modeled seismicity rates. We finally analyze how the swarms occur, in relation with the development of the seismic sequence.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Collocation tests of nodal sensors

DOI: 10.57757/IUGG23-1155 - LINK

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Recently low-cost, easily deployable nodal sensors initially developed for the petroleum industry, are widely used by seismologists to sample the seismic wavefield in dense arrays at unprecedented spatial resolution, and push the limits of resolution in microseismic events monitoring and subsurface imaging. With the increasing demand on the nodal sensors in the industry and seismological community, multiple commercial models of nodal sensors appear in the market and it becomes important to know the potential limitations and variabilities among these models. We conduct a number of laboratory and field experiments to better identify their fidelities. First, we carry out the shake-table tests to identify the sensitivities of these units, which enables us to convert sensor output to units of ground motion reliably. Then we estimate the self-noise of these sensors in a huddle test based on the three-sensor method, which defines the lowest signal that the sensor can discern. Finally all the models are deployed at several field sites for about one month, both the earthquake waveforms and green's function retrieved from ambient noise are compared to show their differences.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Automatic induced seismic event detection in low-seismicity areas

DOI: 10.57757/IUGG23-0469 - LINK

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Seismological phase detection is a fundamental part of seismic observation process. The wave arrival tracking is complicated in sparse seismic arrays over low-seismicity areas, where the noise floor is high and signal-to-noise ratios are low. Classic automatic routines can fail to detect or falsely detect too many of the small induced seismic events.

In this research we compare the results of multiple automatic and machine-learning based phase picking algorithms around Baltic States. In a region of low seismicity, we intend to track induced events, occurring from military exercises and mining blasts. We analyze 11 seismological station data of year 2021 and compare manual phase picks against automatically detected ones. For phase detection we use variations of STA/LTA and deep neural network pickers from Ross et al., 2018 and Zhu & Beroza, 2018.

We show that automatic picking routines coincide very well with manual observations. Even regionally untrained neural networks outperform manual observations, resulting in increased event detections. Neural networks picks are also less susceptible to seismic noise than classic STA/LTA variations, however, false-detection problem cannot be eliminated entirely. We believe that improvements to neural network models could be made, retraining the model using local data or adjusting hyperparameters to better fit the low signal-to-noise ratios of the induced events.

References:

Ross, Z. E., Meier, M.-A., Hauksson, E., & Heaton, T. H. (2018). Generalized Seismic Phase Detection with Deep Learning. *Bulletin of the Seismological Society of America*, *108*(5A), 2894–2901

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

AI-based anatomy of the continuous seismic wavefield at Sos Enattos (Sardinia, Italy) over one year of data

DOI: 10.57757/IUGG23-4332 - LINK

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Sardinia is a seismically quiet region: for this reason, it has been proposed as an excellent location to host fundamental physics experiments requiring low seismic ambient noise such as the Einstein Telescope, the third-generation gravitational wave observatory. In the framework of the instrumental deployment to characterise the formerly lead and zinc mine of Sos Enattos, currently dismissed and converted to a low-noise laboratory, we focus on the link between the records from seismic stations in different locations and the meteorological records collected in their vicinity. To do this, we use a scattering network, a convolutional neural network with wavelet filters, to extract relevant spectro-temporal features at different time scales of the signal. We then use a dimensionality reduction algorithm to reduce the features' dimensions and apply a hierarchical clustering algorithm to identify patterns in the continuous seismic data. We choose hierarchical clustering because it allows us to understand the inter-cluster similarity. We finally investigate the link between these clusters and the external meteorological data collected nearby and reveal the mutual information between the two datasets.

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S04 - Posters - Advancements in Acquisition, Processing and Interpretation of Seismological Data

Understanding and Mitigating the Spatial Bias of Earthquake Source Imaging with Regional Slowness Enhanced Back-Projection

DOI: 10.57757/IUGG23-2185 - LINK

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We investigate characteristics of spatial biases in the Back-projection method and the effectiveness of the Slowness Enhanced Back-projection (SEBP). The spatial bias refers to the location error in Back-projection caused by travel time errors due to 3D Earth structure. SEBP reduces such bias by calibrating the gradient of travel time (slowness) in the source. We first analyze 22 M4-M6 earthquakes in the Commander Island and find the amplitudes and directions of spatial biases follow distinct regional patterns. In light of this, we propose a regional SEBP approach that introduces spatially variable slowness correction. The regional SEBP in the Commander Island resulted in a ~ 50% reduction in the average length of spatial bias from ~20 km to ~10 km, which is more effective than the uniform SEBP that gives a 25% error reduction. We then analyze 109 M4-M7 earthquakes in the Tohoku region and also find a 50% error reduction by regional SEBP. This indicates that half of the spatial biases are aleatory uncertainties that are caused by regional structural complexity and can be calibrated with SEBP, while the residue errors are epistemic uncertainties that are random and caused by local velocity heterogeneities. With regional SEBP applied to the 2011 Tohoku earthquake, we find that high-frequency radiators did not reach beyond the down-dip limit of interplate seismicity, indicating that the coseismic slip unlikely penetrated into the brittle-ductile transition zone. Such observations suggest that the enhanced dynamic weakening mechanism due to thermal pressurization effects may not be activated during this event.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Denoising of Rayleigh Waves to improve DAS processing of urban noise

DOI: 10.57757/IUGG23-3793 - [LINK]

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[2]*TU Berlin, Institute for Applied Geosciences, Berlin, Germany*
[3]*University of Potsdam, Institute of Geosciences, Potsdam, Germany*

Seismic methods have been widely used to image the subsurface for geological characterization and exploration. Due to the limitation of active experiments in populated areas, methods tapping the existing ambient noise as a source of excitation have gained increasing attention. The combination of this approach with Distributed Acoustic Sensing (DAS) is particularly appealing as vast telecommunication networks can potentially be used as sensors. However, seismic noise in urban areas is complex. Usually it is of anthropogenic nature and dominated by traffic. To extract coherent signals from recorded noise, the acquisition of long time series associated with high computational costs is required.

In the study presented, we analyzed the cultural noise along an urban road in Berlin. DAS data was collected at a spatial period of 8 m and a temporal frequency of 1000 Hz along a 3-km long segment of a dark telecommunication fiber. The recorded noise contains transient signals with frequencies between 1 and 40 Hz attributable to the passage of trains. As these signals inhibit the extraction of coherent Rayleigh Waves, we applied a denoising method based on the harmonic-percussive separation technique prior to the standard ambient noise pre-processing (data decimation, band pass filtering, temporal and spectral normalization, cross-correlation) . We compare processing results with and without denoising and conclude that our approach leverages the recorded data better and yields improved virtual shot gathers . This implies the possibility to conduct shorter campaigns for acquiring equivalent results with respect to ambient noise analysis.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Utilization of amplitude values from seismic waveforms recorded by DAS along a bullet train

DOI: 10.57757/IUGG23-4058 - LINK

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[3]National Research Institute for Earth Science and Disaster Resilience NIED, Earthquake and Tsunami Research Division, Ibaraki, Japan

Distributed acoustic sensing (DAS) allows for the deployment of a few tens of meters of seismometers along the length of the optical fiber cable. However, the data obtained from DAS, particularly amplitude information, can vary based on the installation environment of the optical fiber cables. Our proposal is to conduct seismic observations using DAS with optical fiber cables. In this study, we applied DAS to the cable along the bullet train in Kumamoto prefecture, Japan, where aftershocks from the 2016 Mw7.3 Kumamoto earthquake are still highly active. We successfully observed strong motions of the Mj6.6 earthquake on January 22, 2022 in Hyuga-nada and several small local earthquakes for distances over 75 km. An accelerometer that simultaneously recorded the event observed a maximum acceleration of approximately 80 gal. The shaking map (maximum strain distribution) for Mj6.6 was estimated by correcting for cycle skipping caused by the dynamic range. The differential phase data indicated cycle skipping at various channels. We estimated the data from cycle-skipped channels using data from adjacent channels that were not cycle-skipped. The attenuation properties of local earthquakes were identified by correcting for site effects, coupling, and amplification of seismic waves by the railway structure. We observed that the peak strain values as well as PGV decreased with increasing hypocenter distance for each magnitude category. Our results indicate that accurately correcting DAS amplitude values can allow for empirical estimation of earthquake magnitude.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

NORFOX versus NORES: A comparison of seismic events recorded on a co-located DAS and seismometer array

DOI: 10.57757/IUGG23-3861 - LINK

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Distributed Acoustic Sensing (DAS) is becoming increasingly popular for different seismological applications due to its high spatial sampling and potentially long cable lengths. So far, the ability of DAS records for seismic array processing has not been assessed systematically with observed data. We use one month of continuous data recorded on the newly deployed NORFOX DAS array in southern Norway, which is co-located with the 16-element NORES broadband seismic array. NORES has a current aperture of approximately 1.4 km. NORFOX consists of a total cable length of approximately 8 km arranged in 5 arms, with an array aperture of 3 km. Data were acquired from three branches of the array using two DAS interrogators for the full month of February 2023. We analyze this unique data set by first comparing waveforms and signal to noise ratios (SNRs) of local, regional and teleseismic events detected on NORES with the DAS records. We then apply beamforming to the DAS data to evaluate SNR improvements for P and S wave beams deployed for all recorded events. Finally, results of Frequency-Wavenumber analysis of NORFOX and NORES data are compared. We test the findings of a previous theoretical study on DAS array processing which considers the broadside sensitivity of the cable and give a final evaluation of the potential of using DAS arrays for continuous seismic monitoring.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Combined fiber-optic monitoring technologies to assist borehole completion

DOI: 10.57757/IUGG23-1486 - [LINK]

Johannes Hart[1], Christopher Wollin[1], Martin P. Lipus[1], Charlotte Krawczyk[1]
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Reliable well completion and monitoring technologies are a prerequisite to achieve safe, sustainable and efficient use of geothermal reservoirs. Since borehole completion is a high-risk process, we tested how distributed fiber optic sensing technologies can aid monitor the completion process continuously in space and real time. To evaluate the success of the operation conventional well logging tools and other methods can only be used after the completion and show snapshots of discrete points in time.

We present results from a case study in Berlin, where a 450 m deep exploration well was completed for Aquifer Thermal Energy Storage (ATES) purpose. To simultaneously measure distributed temperature (DTS) and distributed elastic and static strain (DAS and DSS) a fiber optic cable was installed behind the production tubing. The combined evaluation of the different fiber optic technologies evidences the potential to observe previously untraceable processes, such as changes in subsurface flow paths due to clogging. Further, the unwanted process of caving can be identified and the rise of gravel or cement observed. This allows to react on site, and subsurface risks will be considerably mitigated.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

A metadata exchange model for Distributed Acoustic Sensing (DAS) by the DAS-RCN data management team

DOI: 10.57757/IUGG23-3156 - LINK

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Institute of Geophysics and Planetary Physics- Scripps Institution of Oceanography, San Diego, USA

Distributed Acoustic Sensing (DAS), with its high-spatial and temporal resolution, low cost-per-sensor, and versatility, could transform how future geophysical surveys and network monitoring are performed, both on land and subsea. DAS, however, is still a relatively new sensing technology and features such as sensor response, calibration, and impact of installation environment are active areas of research. The need to compare measurements across deployments and make the data reusable by others warrants a standardization of DAS metadata in a machine-readable format. The capability to facilitate high-performance computing in a cloud environment is also highly desirable.

Long-standing metadata models developed for seismic data e.g., SEED, SAC or SEG-Y do not adapt well for DAS due to fundamental differences in sensor and data acquisition parameters. There may be thousands of measurement locations in one experiment, the installation environment can vary significantly along the cable, data acquisition equipment and parameters can be changed during an experiment or between repeated surveys. The optical fiber itself has intrinsic properties that influence measurements, and multiple fibers might be used over the course of an experiment or long-term monitoring project. We outline a proposed metadata model that could accommodate most deployment scenarios. The model can be represented in a JSON format but could be readily translated to XML and incorporated into hierarchical data formats such as HDF5 or Zarr. The model aims to enhance the interoperability of DAS data sets, maintain compatibility with more complex industry standards such as ProdML, and build reproducibility into DAS data products.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Investigating dynamic range of Distributed Acoustic Sensing and introducing a neural-network-based detection for saturation effects

DOI: 10.57757/IUGG23-2727 - LINK

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[4]University of Potsdam, Institute of Mathematics, Potsdam, Germany
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[6]National Central University, Earthquake-Disaster & Risk Evaluation and Management E-DREaM Center, Taoyuan, Taiwan Province of China

Distributed Acoustic Sensing (DAS) is used to record high-spatial resolution strain-rate data. For ground motion observation, the DAS data can be converted from strain rate to acceleration or velocity by array-based measurements with coherent plane waves. DAS provides an opportunity to map high-resolution shaking patterns near faults. We installed collocated geophones and optical fiber in Hualien City (a very seismically active area in Taiwan) from the end of January to the end of February in 2022. Earthquakes with magnitudes (Mw) between 3.2 and 5.4 have been recorded. These records illustrate the typical magnitude-distance dependence of ground-motion but also show saturation for higher magnitudes and/or at shorter distances (e.g for an earthquake of Mw 5.2 earthquake recorded at 100 km). For frequency-based analyses, clipped signals on DAS result in challenges not present in classical instruments (seismometers). The upper limit in dynamic range of seismometers results in easily identifiable trapezoidal signals. The dynamic range of DAS interrogators is limited by gauge length, sampling frequency, and wrapped phase in the interferometric phase demodulation. We observe that clipped DAS signals not only affect time series but also contaminate their spectra on all frequencies, due to the random nature of clipping in DAS—contrasting to the flat plateaus in clipped time series on seismometers. Therefore, the identification of the start and end points of clipped DAS records poses a major challenge, which we aim to resolve with a neural network. This approach enhances the efficiency for quality control of massive DAS datasets.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Characterizing Alpine Fault seismicity and geometry at Haast (South Westland, New Zealand) using distributed acoustic sensing

DOI: 10.57757/IUGG23-3149 - LINK

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[1]Australian National University, Research School of Earth Sciences, Canberra, Australia
[2]Victoria University of Wellington, School of Geography- Environment- and Earth Sciences, Wellington, New Zealand

We introduce a Distributed Acoustic Sensing (DAS) array deployed for one month between February and March 2023 and which utilized ~25 km-long telecommunication fibers running roughly parallel and perpendicular to the Alpine Fault near Haast. A key goal of this DAS deployment and planned further work is to improve characterization of natural hazards in southern New Zealand including Alpine Fault seismicity and rockfalls, and to demonstrate the feasibility of DAS studies using dark commercial telecommunications fibers in New Zealand. DAS, with its high spatial (~1 m) and temporal (1 kHz) resolutions, can improve the detection of weak seismic sources, including low-magnitude earthquakes diagnostic of fault activity, rockfalls and avalanches in remote mountainous region, and sediment transport in river systems. The dense sensor deployment across the Alpine Fault further allows us to make high-resolution images of the fault zone including the near-surface fault geometry and velocity structure across the Alpine Fault where it crosses the sole highway in the area. The DAS acquisition was scheduled to coincide with the operation of the ~450 km-long Southern Alps Long Skinny Array (SALSA), which includes 45 mostly broadband seismometers installed 10–12 km apart within ~3 km of the fault trace, to provide new opportunities for interpreting DAS and conventional seismometer data to study seismicity and fault geometry.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Site characterization using H/V spectral ratios from combined DAS and broadband ambient noise measurements on Mt. Etna, Italy

DOI: 10.57757/IUGG23-4463 - LINK

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[2]University of Potsdam, Institute for Geosciences, Potsdam, Germany
[3]Instituto Nazionale di Geofisica e Vulcanologia INGV, Osservatorio Etneo, Catania, Italy
[4]Technical University of Berlin, Institute for Applied Geosciences, Berlin, Germany

Horizontal-to-vertical (H/V) spectral ratios have proven to be an inexpensive and easy tool to gain insight into local site effects. Here we attempt to extend the method to distributed acoustic sensing data by combined processing of records from an array of 26 broadband seismometers and a 1.5 km long fibre optic cable on the North-East flank of Etna volcano. Using the same processing steps as for conventional H/V computing on seismometers, we derive spectral ratios along the trajectory of the fibre.
Results show, that this approach is suited to assess the site response in higher spatial resolution than with broadband seismometers only. The H/V peak frequency distribution generally agrees with results from the array, in some parts indicating otherwise not resolved geological structures. Localized strong amplitude changes in the spectral ratio, coincide with the cable crossing known fault zones.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

DAS Istanbul: From detecting the 2023 East Anatolian earthquakes to full-waveform inversion with dark fibers.

DOI: 10.57757/IUGG23-2693 - LINK

Ali Shaikhsulaiman[1], Daniel Bodwen[1], Andreas Fichtner[1], Ebru Bozdag[2], A. Ozgun Konca[3], Semih Ergintav[3], Esra Ertan[3,4], Evrim Yavuz[4], Isra Bostancioglu[4], Muhammed Ünlü[4]
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[2]Colorado School of Mines,
Department of Applied Mathematics and Statistics and Department of Geophysics, Golden, USA
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[4]Istanbul Metropolitan Municipality,
Department of Directorate of Earthquake and Ground Research, Istanbul, Turkey

Distributed acoustic sensing (DAS) has an exceptional potential of high temporal and spatial resolution capable of revolutionizing geophysical ground motion measurements. Furthermore, existing telecommunication fiber-optic cables, “dark fibers”, offer cheap seismic measurement system particularly in a challenging and busy urban city, such as Istanbul. In this piece, we present results of data recorded by the first 8km segment of a 30km long dark fiber, along the Anatolian side of Istanbul. This includes recordings of the recent East Anatolian earthquake in Turkey, 6th of February 2023 with magnitude M_w 7.8, and its aftershocks.

Using the same recorded data, we additionally aim to present initial results of applying a novel workflow that combines advantages of DAS recordings with recently developed waveform imaging techniques. Our goal is to build a comprehensive initial 2D shallow shear velocity model using a trans-dimensional Bayesian inversion of dispersion curves obtained from ambient noise interferometry. Constrained by available geological and engineering knowledge, the initial 2D shear velocity model will serve as an input for preforming an ambient noise full waveform inversion (FWI), to produce a high-resolution accurate model. The result is expected to greatly increase the understanding of the city's shallow subsurface (first hundred meters) and the assessment of its seismic hazard maps.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

DAS for Regional Earthquake Monitoring in Athens, Greece

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In recent years, it has become clear that Distributed Acoustic Sensing (DAS) is capable of capturing many seismic signals, including earthquakes across a range of magnitudes. Given the vast networks of fibre optic cables beneath urban areas, there is great potential for the utilisation of existing telecommunication fibres for the purpose of seismic monitoring and hazard analysis. However, it is crucial that we first understand the capabilities and potential limitations of applying DAS in this way.

In late 2021, we collected over one month of urban DAS data beneath North-East Athens, Greece, using ~ 24 km of telecommunication fibre owned by the OTE group. This urban dataset contains a broad range of signals, including local anthropogenic activities, as well as numerous seismic events.

We build a catalogue of events observed within the DAS data, and assess differences between our DAS event catalogue and that of the regional seismic network managed by the National Observatory of Athens (NOA). This includes an analysis of to what extent sensitivity to events is influenced by event magnitude, depth, distance and azimuth. The dense spatial sampling offered by DAS facilitates the use of novel array processing methods, which can be used to detect smaller events. We determine whether the benefits of using DAS and applying such methods within a regional seismic network justify the additional costs.

We also explore the influence of the exact fibre deployment and local geological conditions on the seismic events recorded, and how this information can be considered for future DAS earthquake-monitoring experiments.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Detection of microearthquakes triggered by hydraulic fracturing using time- and frequency-domain DAS-trace stacking techniques

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In our study, we analyzed high-frequency DAS data from the FORGE EGS facility in Utah to develop signal-stacking-based detection algorithms for detecting microearthquakes triggered by hydraulic fracturing.
In terms of data structure, it is found that the DAS data considered is constituted by a high-frequency coherent noise, while microearthquakes are characterized by irregularities of this noise structure in the time- and frequency-domain.
We evaluate different preprocessing steps (e.g., different frequency-filters, trace-normalisations, coherent noise supression methods,...) with the goal of improving the SNR of stacked DAS-quantities.
It turns out that, that unlike in conventional seismic signal-stacking, the components of the background noise do not cancel each other out during summation in the time-domain. Instead, the numerous frequencies of background noise interfere with each other, which causes respective large noise peaks in sections of particularly strong constructive interference, which is an additional limiting factor of the detection threshold.
In addition, we used the Power-Spectral-Density (PSD) method, that analyzes the signals in the frequency-domain.
We show, that the background noise interference do not occur during stacking of PSD-traces, since it neglects unwanted frequency-components in the calculations before summation. However, the PSD method responds to another DAS-data characteristic noise-burst-type, that is not resolved by the stacked quantities in the dime-domain.
We present an detection algorithm, which superimposes the individual threshold exceedances of time- and frequency-domain DAS-stacks, to filter both observed noise sources from the results.
This algorithm was tested on a subset of 3-hours continuous recordings, where it captured all microearthquakes with magnitudes greater than -1.4 with a reliable true/false ratio.

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Railway communication lines as a network for earthquake monitoring and near-surface characterization - a case study

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Distributed Acoustic Sensing (DAS) is increasingly being used in various applications and is gaining particular importance in rail and train monitoring. When connected to an optical fiber, DAS systems create a reliable solution for continuous monitoring, that can often be used with the existing optical fiber cable infrastructure. Besides being an effective complement or even replacement for conventional rail monitoring techniques, DAS can be used as a powerful data acquisition tool for understanding different underground geological processes. In this case study, we describe the use of a DAS system connected to an optical fiber cable installed parallel to a railway for use as a distributed sensor for seismic monitoring. Railway lines in Europe form a dense network, which mostly have telecommunication FO-cable running parallel to the network. Utilizing these lines for DAS monitoring could provide an important contribution to seismic observations. This case study discusses how fiber coupling, length and spatial position of monitored object together with the DAS configuration parameters can affect the data. Within the current project, the DAS was connected to ~40 km of fiber along an L-shape track and data was acquired with a frequency of 1 kHz and a spatial sampling interval of 5 m. Due to the L-shaped track, both perpendicular and parallel incoming earthquake wave fronts to the fiber could be recorded. The acquired data clearly show the different seismic waves arrivals. Besides earthquake monitoring, DAS-equipped railway network has a great potential for near-surface characterization, allowing geological processes to be monitored in time.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Three-dimensional Distributed Acoustic Sensing at the Sanford Underground Research Facility (Lead, SD, USA)

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Distributed Acoustic Sensing (DAS) has proven to be a valuable tool for monitoring seismic signals by providing high spatial and temporal resolution sensing of dynamic strain along fiber optic cable. Furthermore, every DAS channel records the seismic wavefield essentially synchronously at each sampled time because the interrogator samples each channel at the speed of light in the fiber. Here we investigate the capabilities of a unique, subsurface, three-dimensional array with spiral-like portions in the Sanford Underground Research Facility (SURF), the former Homestake mine, between 1250- and 1478-m depth for detecting local, regional, and teleseismic sources of ground vibrations. Our pilot array finds that DAS records high-frequency (above 5 Hz) vibration sources, including mine activities and local and regional blasting events. Furthermore, we find that fiber resting on the surface with rocks placed every meter or so may contribute to low-frequency noise that contaminates the interpretation of teleseismic waves, particularly lower-frequency S-wave arrivals. Finally, this loosely coupled cable was compared with a 200-meter section grouted in a shallow saw-cut groove for sensitivity and noise levels. This three-dimensional DAS array provides significant data for future analysis and for improving and expanding the DAS array in SURF.

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S05 - Posters - Advances in Earthquake and Explosion Monitoring Using Distributed Acoustic Sensing

Loops of slack in dark fiber and their effect on interferometric analysis of ambient noise – symptoms, consequences and remedies

DOI: 10.57757/IUGG23-4886 - LINK

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With the development of Distributed Acoustic Sensing (DAS), vast telecommunication networks hold the potential to serve as dense seismic sensor arrays. As such, they may facilitate the seismic microzonation as well as exploration and monitoring of utilizable and utilized subsurface volumes at favorable costs – particularly in densely populated areas. However, numerous technical aspects remain under investigation to further maturate this innovative seismological approach.

In this study, we investigate how loops of slack fiber affect the results of passive ambient tomography, a particularly appealing exploration approach due to its low footprint. We present results obtained with DAS recordings on both purposefully installed as well as dark telecommunication optic fiber. Sledgehammer blows were recorded on an optic fiber laid out in an urban heating tunnel before and after introducing several loops of slack. Discontinuous wavefronts can be observed once the arclength of the coiled fiber exceeds the gauge length. Similar observations were made on the virtual shot gathers calculated along a 4.5 km long segment of dark fiber along a major road in the city of Berlin, Germany. We present how the results of ambient noise tomography along this linear DAS array are affected by the presence of loops of slack.

We conclude that DAS channels recording within a loop of slack can be identified during the data processing and require removal prior to final processing.

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S06 - Posters - Pre-Instrumental Earthquake Data

Evaluating the performance of Intensity Prediction Equations for the Italian area

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[2]Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Pisa, Italy

Intensity Prediction Equations (IPEs) allow predicting the possible macroseismic intensity values at any site, as a function of epicentral distance and epicentral intensity or magnitude. In Italy, different approaches have been proposed in the last years for developing intensity attenuation models. We evaluated the performance of the five most recent IPEs valid for the Italian area comparing their predictions with intensities documented at Italian localities.

We built two different testing datasets using the data contained in the most recent versions of the Italian Parametric Earthquake Catalogue CPTI15 and of the Macroseismic Italian Database DBMI15. Dataset 1 contains 213 earthquakes with instrumental location and magnitude from 1907 to 2020, whereas Dataset 2 includes 357 events that occurred from 1117 to 1978 with the epicentral parameters estimated from macroseismic intensity data. We computed the residuals between documented intensity values and predicted intensities using the IPEs. Analyzing these results as a function of the epicentre-to-site distance, of the values of documented intensities and of the magnitude of each considered earthquake, we observed a systematic underprediction for high intensity values in both datasets for all the considered IPEs.

We also investigated the between-event residuals to highlight spatial and temporal patterns. The results did not show any particular spatial trends, but a significant temporal dependence of the results for Dataset 2, with an underestimation of the documented values for all the considered IPEs for earthquakes in the period 1000-1700.

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S06 - Posters - Pre-Instrumental Earthquake Data

Re-evaluation of the earthquake of 10 February 1871 in the Northern Upper Rhine Graben, Central Europe, and its aftershocks

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On 10 February 1871, a damaging earthquake of intensity VII EMS occurred in the former Grand Duchy of Hesse (today State of Hesse, Germany) at about 05:30 local time. The earthquake in the Upper Rhine Graben near Lorsch has been the subject of several individual investigations (e.g. Landsberg 1933; Gutdeutsch, Hammerl 1999). Within the framework of a study by the Federal Institute for Geosciences and Natural Resources, Germany (BGR), this earthquake and its aftershocks were re-investigated. 85 contemporary newspapers were evaluated, containing about 210 reports on the main earthquake. The newspaper reports were evaluated with regard to their quality according to the criteria time of writing of the report, indication of times and places, extent of macroseismic observations, eye-witness report, and grades from poor to good were assigned. In addition, archival research was conducted in Darmstadt, Strasbourg and Lorsch, which, however, yielded only a few additional sources. For 125 locations, the macroseismic observations of the main earthquake are suitable to assign intensities (≥ III). The information on the main earthquake is satisfactory, despite the Franco-Prussian War of 1870/71, which took up a large part of the newspapers' coverage at the beginning of 1871. The written record of aftershock reports is considerably worse, apart from two stronger aftershocks on 12 and 25 February 1871 (intensity VI EMS). For the period from 10 February to 19 March 1871, 55 aftershocks were identified, of which only 11 had been recorded in earthquake catalogues so far.

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S06 - Posters - Pre-Instrumental Earthquake Data

The "ArChaeology, inventory of RecOnstruction, Seismology and Structural engineering » ACROSS project

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[11]Institut de Radioprotection et Sureté Nucléaire, Bureau d'évaluation des risques sismiques pour la sureté des installations, Fontenay aux Roses, France

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Historical earthquake catalogs are one of the building blocks for the assessment of seismic hazard. Despite many years of research in the archives, many earthquakes remain poorly known. New sources of informationare hence required.

Among these, historical buildings are witnesses of natural catastrophes recorded in their walls as structural disorders, repairs, and restorations. Our project aims to study past earthquakes using buildings as "stone seismometers", analyzing the seismic ground motions required to explain building repairs/disorders, or their absence. The goal is to demonstrate that archaeological characterization of post-seismic repairs on buildings can be successfully used to infer key ground motion and earthquake source characteristics of historical earthquakes.

An interdisciplinary connecting "ArChaeology, inventory of RecOnstruction, Seismology and Structural engineering" (ACROSS) is introduced to gain such knowledge. Based on innovative techniques to inventory repairs in the building archaeology; seismic input signals consistent with the seismotectonic context; digital building models implementing realistic geometry and construction materials as well as robust modelling of masonry behaviour, the ACROSS method is declined in five steps,

1. Collecting the data produced by the archaeology of the buildings and the study of historical sources.

2. Identification of damage mechanisms.

3. Definition of the digital building model used for seismic dynamic analysis.

4. Comparison of the numerical analysis results, based on previous steps, with repairs and damage mechanisms.

The method is applied to six bell towers located in the Mugello basin (Tuscany, Italy). They were affected by many historical earthquakes at least from the middle of the 16th century.

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S06 - Posters - Pre-Instrumental Earthquake Data

Reanalysis of historical earthquakes - case study: The great Zagreb (Croatia) 1880 earthquake

DOI: 10.57757/IUGG23-0370 - LINK

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In areas with medium to moderate seismicity, data on historical earthquakes are crucial in the seismic hazard assessment. Therefore, it is necessary to invest considerable effort in their verification and/or reanalysis. In March 2020, the city of Zagreb (Croatia) was hit by an earthquake of magnitude 5.5 (certainly the strongest one in the last 100 years, and perhaps the strongest after the Great Zagreb 1880 earthquake). Its analysis provided interesting information about the geodynamics of the wider Zagreb area and the Medvednica Mt. Due to these findings, the reanalysis of the Zagreb 1880 event (of magnitude 6.0, and which largely defines the seismic hazard of northwestern Croatia) proved to be a necessity. A detailed macroseismic survey was carried out again, resulting in a new intensity map. Macroseismic field modeling and comparison with empirical intensities were also done, and new geophysical measurements were performed. Based on all the collected information, it can be concluded that the 1880 earthquake was caused by a similar mechanism as in the case of the 2020 earthquake (with hypocenter location in an almost identical place). However, there is a possibility that shortly after the main earthquake there was an aftershock whose location was several kilometers western than the location of the main earthquake. These resulted in the observation of cumulative intensities (cumulative impact of the main earthquake and the strongest aftershock), which has an implication on the epicentral intensity assessment of the main earthquake.

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S08 - Posters - Anthropogenic Seismicity

Preliminary Shallow depth estimation by HVSR in Nova Ponte Dam

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Reservoir-Triggered Seismicity is an unnatural phenomenon, recorded concomitantly and/or after the filling of a hydroelectric plant reservoir, where previously there was no record of seismic activity. The local geology is commonly the main parameter for seismic risk analysis, although recent studies suggest that the environmental noise also plays an important role. Thus, a study of the local response analysis was carried out in the hydroelectric reservoir in Nova Ponte, in the state of Minas Gerais. This reservoir was selected because it is classified as a case of seismicity triggered by the reservoir. Data was collected with short-period and broadband seismometers in 74 stations with spacing up to 2 km. These measures were used for the calculation of the Fundamental Frequence (f0) using the Nakamura technique, from which the depth of layers could be constrained. Layer-depth values could be compared with previous seismicity and microzonation maps, as well as with geological structures. From the correlation of shallow crustal structures (such as faults) with layer-depths, it is possible that these structures can be forced by the change of direction and intensity in the field of local tensions, generating the seismicity events triggered by the reservoir.

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S08 - Posters - Anthropogenic Seismicity

Methodologies for the AssessmenT of anthropogenic environmental hazard: Induced Seismicity by Sub-surface geo-resources Exploitation (MATISSE)

DOI: 10.57757/IUGG23-3570 - LINK

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The goal of MATISSE is to develop and implement technologies needed for successfully detecting and quantifying hazards connected with geo-energy operations in the sub-surface, in particular induced seismicity. Anthropogenic earthquakes constitute one of the major environmental impacts associated with geo-resources exploitation. Injection induced events are an undesired dynamic rockmass response to technological processes. Water injection operations taking place during industrial activities such as oil, gas and geothermal exploitation often induce microseismic activity and, under specific circumstances, reactivate existing faults, causing events of considerable size. These industrial activities can also determine air pollution and ground water contamination.
Induced seismic hazard is evaluated through the computation and update of ground motion prediction equations, the time-lapse of velocity, attenuation and seismic noise tomography and the computation of pore pressure time variations. All these parameters are correlated with operational activities. A multi-hazard approach aimed at evaluating the adverse effects on environment caused by the sub-surface exploitation of geo-resources is developed.

This work has been supported by PRIN-2017 MATISSE project, No 20177EPPN2, funded by Italian Ministry of Education and Research.

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S08 - Posters - Anthropogenic Seismicity

Sources of vibrations within buildings – a case study from Johannesburg

DOI: 10.57757/IUGG23-2688 - LINK

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Following the experience of significant vibrations felt in a multi-storey office, the Council for Geoscience (CGS) was requested to monitor and record the vibrations in an effort to determine its source. The vibrations on the premises were monitored by means of five temporary seismograph stations, with two in the office building and three located around the premises. From the start of the analyses, it was very clear that the sensors installed at the sites located around the premises did not record the vibrations documented by the staff within the building. The sites within the building did record the vibrations, but the vibrations did not exceed the limits of the international standards. Thus, the source of the vibration was either within the building, or very close to the building. Alternatively, the vibration may originate further from the building but may coincide with one of the natural frequencies of the building or its components thereby amplifying the vibrations. The frequency of almost 7 Hz was surprisingly low and indicated that it is unlikely caused by machinery in the building which is typically at higher frequencies.

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S08 - Posters - Anthropogenic Seismicity

Human-induced earthquakes in the Zagros fold-and-thrust belt, Iran

DOI: 10.57757/IUGG23-0172 - LINK

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The Arabian Plate's convergence towards Eurasia led to the building of the Zagros fold-and-thrust belt. This region is one of the most seismically active mountain ranges and the greatest loci of oil and gas production on Earth. The folded and faulted sediments of Zagros contain 90% of Iran's proven hydrocarbon reservoirs including the world's second-largest gas reserves, ~17% of Earth's total. Although Zagros is known as a naturally elevated seismicity zone, the occurrence of anthropogenic earthquakes has been reported in some studies (e.g. attributed to reservoir impoundment, mining, and groundwater pumping). Here, using geodetical and seismological measurements and models, I report the different cases of induced seismicity related to operations in the gas and oil fields of Zagros. Because of the significant number of highly productive hydrocarbon reserves in Zagros, studying seismicity from a new point of view is essential in this region. However, discrimination of anthropogenic earthquakes from natural events in the Zagros is challenging, and detailed source analysis, notably the determination of the depth of earthquakes is required to discriminate.

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S08 - Posters - Anthropogenic Seismicity

Microseismic event and phase detection using deep learning and clustering methods

DOI: 10.57757/IUGG23-4154 - LINK

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[3]*ETH-Zurich, Swiss Seismological Service, Zurich, Switzerland*

Microseismic monitoring is an important tool to characterize the reservoirs and delineate the growth of small-scale fractures. In addition, microseismic events are crucial for describing detailed fault geometries, stress changes, and spatial-temporal evolution of seismogenic activities. Deep learning has been extensively and successfully utilized for seismic event detection and phase picking. In this work, we propose an integrated workflow of waveform denoising, event detection, and seismic phase detection based on convolutional neural network (CNN) and unsupervised clustering, aiming at identifying and classifying microseismic P- and S-wave arrivals accurately. First, we preprocess (e.g., bandpass filter) the continuous waveforms and extract statistical features, and then feed the features into CNN for deep feature extraction and learning. The microseismic phase detection is then performed using clustering from waveform feature distance (similarity), which is retrieved from both statistical features of waveforms and the deep features extracted by CNN, yielding microseismic P- and S-wave arrival detections. We use synthetic data with different source mechanisms and signal-to-noise ratios, along with field microseismic data collected from the Hengill Geothermal area in Iceland, to verify the effectiveness of the proposed workflow in detecting weak microseismic phases. The refined phase detections also improved the resolution of stacking-based source imaging.

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Near-surface P-wave velocities near West Miami, Florida from quarry blast records

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We used blast records from several limestone quarries in the Miami Lakes area (25.6°N, -80.3°W) northwest of Miami, Florida to estimate shallow P-wave velocities. Prior knowledge of the velocity model was lacking. We deployed a network of ten Raspberry Shake seismometers (six 3-component, four 1-component with collocated infrasound) at residential homes in the Miami Lakes region and visually identified 1639 blasts from July 2019 to February 2023. We manually picked 1450 P-phase and air-wave arrivals using the earthquake analysis software SEISAN. We know the exact locations of 350 blasts (November 2021 to June 2022) from the Miami Dade Pilot Program report and used a subset of 200 blasts with small location uncertainties in our catalog (average difference estimate-to-true: 0.9 km). The blasts occurred in three quarry areas known as White Rock Quarry (WRQ), Cemex, and Titan. We obtained average P-wave velocities from the quarries to the seismic stations of 4.36 to 4.56 km/s via linear regression. Blasts at WRQ that were nearest to the network (2 to 7 km) allow precise picking and result in a well-constrained velocity of 4.36 km/s (R-squared 0.9). Blasts at the Cemex quarries occurred between 1 to 12 km distance and we obtained a velocity of 4.56 km/s. Blasts at the Titan quarries, 8 to 15 km from the network, result in an average near-surface P-wave velocity of 4.45 km/s. The velocities are consistent with expectations for the Pleistocene Miami Limestone that is extracted, and the small variations suggest relatively homogeneous material properties.

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S08 - Posters - Anthropogenic Seismicity

Hydraulic and mechanical properties of fault and host rocks from the Blue Mountain Geothermal Field, Nevada

DOI: 10.57757/IUGG23-1099 - LINK

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[1]*Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum GFZ, Geomechanics and Scientific Drilling, Potsdam, Germany*
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Several target reservoirs for Enhanced Geothermal Systems comprise hot, dry rock lithologies characterized by low matrix permeability. To improve the permeability of these formations and thus to increase the productivity of power plants, hydraulic stimulation is a common practice. For this purpose, water is injected into the reservoir, causing a local change in the effective stress state that can potentially trigger fault slip seismicity. However, seismicity can be triggered even during normal operation, as in the case of the Blue Mountain geothermal field, Nevada, USA. Here, a significant increase in microseismic activity is observed during the annual maintenance shutdown of the power plant pumps, suggesting more complex processes, such as poroelastic stress transfer, contributing to seismicity. To better understand induced seismicity and explore the underlying mechanisms, we conducted triaxial experiments on intact and faulted reservoir rock samples from the DB2 well at the Blue Mountain geothermal site and determined the effective pressure sensitivity of flow and poroelastic properties over a range of pore (<40 MPa) and confining (<50 MPa) pressure conditions. Laboratory results are compared with permeability estimates previously determined from tidal responses in idle wells, supplemented by a seismicity catalog of continuous waveforms records from 2016 to 2019 to identify seismicity migration patterns associated with operational changes. The integration of cross-scale field and laboratory data aims to improve the characterization of the permeability structure of the fault zone at Blue Mountain and to better understand the coupling between matrix permeability, fault zone hydrology and mechanical behavior.

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S08 - Posters - Anthropogenic Seismicity

‘Seismic monitoring of deep geothermal power plants and possible seismic impact’ – results of the joint research project SEIGER

DOI: 10.57757/IUGG23-4087 - LINK

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During hydraulic stimulation as well as during production of deep geothermal wells induced seismicity might occur. To keep perception of seismicity and seismic risk at a low level, the use of local seismic networks is an established monitoring measure. Based on its results, parameters of operation of wells like injection pressure can be adjusted to maintain acceptable levels of seismicity.

The joint research project SEIGER was part of the 7^{th} Energy Research Programme of the German federal government. It was a collaboration of 27 scientists from universities, research institutes and private companies in Germany. Their work included automation of monitoring, optimization of the seismic research network in the area of Landau in the Upper Rhine Graben in southwestern Germany as well as the use of seismic arrays. The latter can serve as supplement or alternative in respect of local seismic networks and they can monitor a larger area than local networks. Geomechanical modelling techniques were extended to investigate possible triggering of existing faults near geothermal wells. Induced seismic events were attributed to existing fault patterns by improvement of seismic location techniques using 3D seismic velocity models. Passive and active seismic methods were adopted to reveal the shallow ground structure and to estimate the possible amplification of seismic motion (site effect) efficiently, for instance in the urban area of Munich. The data base of seismic hazard assessment of induced seismicity was improved in respect of local ground motion prediction equations, temporal changes of seismicity and consideration of site effects.

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S08 - Posters - Anthropogenic Seismicity

Reliability of moment tensor inversion for different seismic networks

DOI: 10.57757/IUGG23-3465 - LINK

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The work investigates the reliability of moment tensor (MT) inversion, a method used to determine the source mechanisms of earthquakes, across four different seismic networks. The study compares the synthetic test results of MT inversion for two underground mining and two artificial reservoir monitoring seismic networks with different geological settings and network geometry. For research, the time domain first P-wave onset amplitude and polarity inversion was applied in synthetic tests. The analysis was performed to assess how the consistency and accuracy of the results depend on different factors like network configuration, velocity model, events depth, focal mechanism of event, and applied noise. The work provides insights into different factors which have to be considered to enhance MT accuracy. The findings highlight the impact of the velocity model in MT inversion. Particular attention was paid for non-shearing mechanisms and the presence of non-shearing components artifacts in inversion results of shearing mechanisms. The influence of variables, especially the network geometry related to depth and data quality on the reliability of moment tensor inversion was described in the context of other considered factors.

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S08 - Posters - Anthropogenic Seismicity

Using deep learning and spectrograms to identify anthropogenic signals in an urban setting

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El Paso, Texas, USA, along with its sister city Ciudad Juarez, Mexico, is the second largest binational city worldwide, and lies in a tectonically-active rift zone: the Rio Grande Rift. The rate of rifting is relatively slow, ~2 mm/year, but historic earthquakes suggest the potential of large earthquakes in the area. From June 5-14, 2021, a 50 Magseis Fairfield Z-Land 5-Hz 3-component nodal seismic network was deployed to record seismic data in El Paso, Texas in order to characterize local site response in an urban setting. We utilize data from this local network to create a seismic event catalog and attempt to differentiate anthropogenic sources from naturally-occurring ones using a suite of approaches, including machine learning, time-frequency analysis, beamforming, power spectral density, and cross-correlation. We first use a deep neural network-based seismic algorithm to identify seismic arrivals from natural and possibly mining events. We then will run an optimized STA/LTA detector to identify emergent, long duration signals, typical of trains, and then compare our results to the train schedule, where train traffic is very active. Trains can also be identified using spectral and beamforming analysis. We will use these techniques to compare our results with those from the STA/LTA and machine learning approaches. Finally, we will compare the differences in energy recorded by stations with variable site surface geology, incorporating signals recorded by a permanent broadband station as a reference.

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S08 - Posters - Anthropogenic Seismicity

Application of machine learning methods to detection and interpretation of reservoir triggered seismicity

DOI: 10.57757/IUGG23-3286 - LINK

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By using machine learning (ML) techniques we can increase the efficiency of the detection of clusters and mapping the rupture areas, which may be further analyzed in the context of the seismogenic process related to local tectonics and hydrogeological background. We are currently seeing an eruption in ML applications from seismology, however, reservoir-triggered seismicity (RTS) has some aspects that require an individual approach. It is mainly due to the following factors: a small number of mainly weak earthquakes limiting the training of deep learning, and seismicity often appears in unexpected areas and as swarms. Above all, such type of seismicity depends on anthropogenic and hydrological conditions. We compared deep learning methods of event detection and location, our own artificial neural network, and other similarity detection methods.
We study also the possibilities of ML in searching for seismic clusters in the time and space domain, in the interpretation of the event locations and focal mechanisms of the repeaters with the tectonics, and in dynamic relationships between hydrodynamic changes and the RTS with the use of recurrent neural networks. This work was supported by research project no. 2021/41/B/ST10/02618, funded by the National Science Centre, Poland under agreement no. UMO-2021/41/B/ST10/02618.

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Seismic Waves Interpretation Program, version 5 (SWIP5), in the interpretation of reservoir-triggered seismicity.

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The Seismic Waves Interpretation Program version 5 (SWIP5) was designed to work in seismological data processing centers, where waveforms from stations are routinely analyzed. This program aims to facilitate the routine analysis of seismic recordings such as manual and automatic phase picking, magnitude counting, focal mechanism, etc. Its development efforts were made to take into account the experience and inconveniences of using the earlier programs for the interpretation of small and induced seismicity.
The SWIP5 program is modular. It consists of a core that enables basic operations and controls modules that can be developed independently of the core, added to, or removed from the SWIP5 package during its lifetime. Thus, the user can create his own functionality of the program. The cooperation of the program with other programming environments also allows creating of extensions in Matlab and Python using ObsPy.
The program was applied to surface water reservoir-triggered and mine-induced seismicity. Cooperation with the industry requires individual interpretation (e.g. counting energy instead magnitude) and the program allows for a particular configuration. We present its application both in the routine analysis of tremors and in the study of the seismicity of these areas. Results are kept in the QuakeML database adopted for anthropogenic seismicity. Some tool allows cooperation with the EPOS Anthropogenic Hazards TCS platform EPISODES (https://tcs.ah-epos.eu/).

The Seismic Waves Interpretation Program version 5 (SWIP5) was designed to work in seismological data processing centers, where waveforms from stations are routinely analyzed. This program aims to facilitate the routine analysis of seismic recordings such as manual and automatic phase picking, magnitude counting, focal mechanism, etc. Its development efforts were made to take into account the experience and inconveniences of using the earlier programs for the interpretation of small and induced seismicity.
The SWIP5 program is modular. It consists of a core that enables basic operations and controls modules that can be developed independently of the core, added to, or removed from the SWIP5 package during its lifetime. Thus, the user can create his own functionality of the program. The cooperation of the program with other programming environments also allows creating of extensions in Matlab and Python using ObsPy.
The program was applied to surface water reservoir-triggered and mine-induced seismicity. Cooperation with the industry requires individual interpretation (e.g. counting energy instead magnitude) and the program allows for a particular configuration. We present its application both in the routine analysis of tremors and in the study of the seismicity of these areas. Results are kept in the QuakeML database adopted for anthropogenic seismicity. Some tool allows cooperation with the EPOS Anthropogenic Hazards TCS platform EPISODES (https://tcs.ah-epos.eu/).

Observation of hydraulic-induced ground deformation from a dense broadband seismic array during a water pumping experiment

DOI: 10.57757/IUGG23-1356 - LINK

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[2]Sinotech Engineering Consultants Inc., Geotechnical Engineering, Taipei, Taiwan Province of China

Underground aquifer pore fluid volume changes can induce ground deformation, detectable by seismometers as ultra-long period tilt signals. To study evolution of the hydraulic-induced ground deformation, we deployed a dense seismic array during a water pumping experiment, which withdrew groundwater from a nearby borehole well in Shuangxi, mountainous region in northern Taiwan. Nine shallow borehole broadband seismometers were installed around the pumping well within 3-40 m away. We conducted two stages of pumping tests: a step-drawdown pumping for 6 hours and later on a 24-h continuous drawdown with a constant pumping rate. In the first stage, the tilt signals from four seismometers near the pumping well show ground bulge with radially directional tilts up to 10 μrad for a drawdown of 10 meters. We interpret the bulge as the crustal response to the unloading of discharged groundwater in this relatively homogenous crust, as imaged by our reflection seismic survey. In the second stage, the tilt signals show that the spatially complex deformation patterns are related to local fracture attitudes. However, the arrayed observation can still detect the deformation enhanced by supplementary water from outside of the array after 6 hours of the continuous pumping. Our study demonstrates that dense broadband seismic arrays may offer a relatively less expensive and non-invasive tool to study temporal and spatial evolution of ground motions and groundwater flow patterns during pumping tests.

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A study on induced seismic activities in southeast of Sichuan basin, China, using a local temporary network

DOI: 10.57757/IUGG23-1089 - LINK

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Induced seismic activity is becoming more and more severe in recent years near the southeast of the Sichuan basin, China, as the rapid development of Shale Gas exploitation around the local area. An M_S 5.7 earthquake occurred near Xingwen County on 16 December 2018 within the Sichuan basin which is the largest hydraulic fracturing (HF) earthquake in China to date and caused ground motions intense enough to be felt, triggered landslides, caused ￥50 million in direct economic losses, injuries, and resulted in the first fatalities. Besides, 8 $M_S \geq 5.0$ earthquakes have occurred Southeast of the Sichuan basin since 2018 supposedly either caused by HF operation or induced by wastewater disposal, where seismic activity has been low historically. The tomoDD double-difference tomography method has been applied to get the high-resolution three-dimensional structures, along with accurate locations of small earthquakes in the study area, taking advantage of 21 mobile stations' temporary network. Combined with the inverted structure and events' location data, along with the local geological structural information, we had a better understanding of the seismogenic structures of some moderate to strong earthquakes that occurred in the Sichuan basin. This study can help to establish a suitable regulation controlling system for the safe development of shale gas resources in the Southeast of the Sichuan basin as there is no one yet to date.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Seismic Hazard Assessment for Sylhet City – A Critical Review

DOI: 10.57757/IUGG23-4192 - LINK

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Sylhet, the 4th largest city of Bangladesh, is located in the north-eastern Division of Sylhet with the highest seismic zone coefficient (Z=0.36) of the recently updated Bangladesh National Building Code (BNBC-2020). Major faults capable of generating large magnitude (M≥7) earthquakes are located within and in the vicinity of the Sylhet Division. Most prominent historical earthquake is the 1918 Magnitude 7.6 Sri Mangal Earthquake with epicenter near Sri Mangal, a town about 75 km south of Sylhet city. The east-west trending Dauki fault along the northern Bangladesh-India border and much closer to the Sylhet city, is also considered as a potential seismic source. A brief review of the research work done related to seismic sources and seismic hazard assessment for Sylhet city is presented. Critical review of published probabilistic and deterministic seismic hazard assessment studies have been performed. More recently, the effect of a large magnitude earthquake on the Dauki fault on the seismic input motion for the city of Sylhet is studied using an advanced version of the Neo-Deterministic Seismic Hazard Assessment (NDSHA) software based on higher frequency computations developed at University of Trieste, Italy. Estimated ground motions from various seismic hazard assessment studies are compared with code provisions of BNBC-2020 and neighbouring Indian building code. Differences exist and the implications of such differences will be addressed. It is concluded that the estimated ground motion may exceed code specified values and more source specific studies need to be carried out for this region.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Frequency content indicators of the ground motion generated by the intermediate-depth earthquakes of Vrancea region (Romania)

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The Vrancea region is one of the most active intracontinental seismic areas in Europe, and main source of seismic hazard in the extra-Carpathian zone of Romania.

The frequency content of the earthquake ground motion is an important characteristic of earthquake loading for the seismic response of engineering systems.

Our study is focused on two frequency content – based parameters: the ground motion dominant frequency and the mean period T_m.

The study data consist of horizontal acceleration records of 19 earthquakes with moment magnitude ≥ 4.5: four strong earthquakes (M_w between 6.4 and 7.4) recorded with analogue instruments in the period 1977-1990, and 15 moderate-size events (M_w in the range 4.5-6.0) digitally recorded in the period 2004-2022.

To point out the relative contribution of the travel path and seismic source to the formation of the frequency content indicators, we examine separately the effects of hypocentral distance, focal depth and earthquake magnitude on the two parameters.

The analysis does not evidence a significant effect of attenuation, up to hypocentral distances of about 350 km. Likewise, no effect of source depth ($85 < h < 150$ km) is detected. The influence of earthquake magnitude is considerably stronger than the influence of distance, while the effect of site conditions is prevailing on the dominant frequency and mean period.

Finally, we develop simple empirical predictive relationships for the investigated parameters. The proposed models predict the frequency content indicators as function of magnitude, focal distance and local site conditions.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

A preliminary analysis for the probabilistic seismic hazard analysis of Southern Tunisia

DOI: 10.57757/IUGG23-0144 - LINK

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[1]*Ecole Nationale d'ingénieurs de Sfax ENIS, Géologie, Sfax, Tunisia*
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Ecole et Observatoire des sciences de la terre EOST, Strasbourg, France

Although located along the Africa - Eurasia plate boundary with about 6 mm/yr NNW-SSE convergence, Tunisia is classified as an area with moderate seismicity. However, with the large historical earthquakes, the probability of occurrence of destructive seismic events can be significant. This work aims to analyze the distribution of seismic sources, and estimate of the seismicity rate in order to establish a seismic hazard map for southern Tunisia. The estimation of the seismic behavior of a source area requires the collection of geological (tectonic and seismotectonic), historical and instrumental seismicity and geodetic data. Recent investigations in active tectonics, GPS results, seismotectonics, paleoseismology and archeoseismology provide new data that are integrated in our analysis. The first step is devoted to the construction of the homogeneous seismicity catalog in moment magnitude (Mw) from the ISC and regional catalogs. Then we integrate the available seismicity, geodetic and tectonic data into a database for the seismic hazard calculation using the CRISIS software. It is then essential to evaluate to what extent the application of methodologies and relate parameters (GMPEs) for the characterization of the seismic hazard, developed in regions with high seismicity (e.g., Italy, Turkey, Algeria, California) is valid for areas with present-day moderate seismicity comparable to Tunisia. The new results show an estimate of the return period, probability of exceedance of ground acceleration that can be injected into the Probabilistic Seismic Hazard Assessment (PSHA), and subsequently in the construction of seismic hazard and risk maps for Tunisia.

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A workflow for rapid time-dependent estimates of earthquake-induced mass-movement likelihood and associated impacts in Switzerland

DOI: 10.57757/IUGG23-4930 - LINK

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Athanasios Papadopoulos[1], *Philipp Kästli*[1]
[1]*ETH Zürich, Swiss Seismological Service SED, Zürich, Switzerland*

Earthquake-induced mass movements are a substantial threat to mountainous areas in seismically active regions like the Valais, the most seismically hazardous region of Switzerland. We present a strategy to deliver rapid time-dependent predictions of mass-movement likelihoods in the Valais and their impacts on lifelines in near real-time during major earthquake sequences. We rely on the Swiss Seismic Hazard and ShakeMap frameworks and on the availability of a Swiss-specific empirical model for the prediction of seismically induced mass-movement likelihoods, and combine them with rapid earthquake shaking estimates based on short-term seismicity forecasts following a triggering seismic event. The obtained probabilities of mass-movement are spatially associated with exposed assets in the region to estimate the associated risk. This procedure can provide stakeholders with alarm levels and other decision-making tools based on risk-cost-benefit considerations for critical lifelines.

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ShakeMap model with deviation correction method of the 21 may 2021 M6.5 Yangbi, Yunnan, China

DOI: 10.57757/IUGG23-1173 - LINK

Kun Chen[1]
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On May 21, 2021, a magnitude 6.4 earthquake struck Yangbi County, Yunnan Province, China. This article used the collected 21 seismometers and the strong seismic observation data of 304 intensity meters, comprehensively considered the geological structure background, source mechanism solution and aftershock distribution of seismic faults. As a result, the ground motion intensity distribution map of this earthquake was quickly calculated using the deviation correction method of magnitude translation. The strong seismic observation data showed that the maximum horizontal peak acceleration was 720.3cm/s^2 observed at the Yangbi Observatory with an epicenter 79km away. The peak horizontal acceleration observed by 14 stations > 45cm/s^{2,}. A large number of long-range, small-scale observation records reflect the ground motion attenuation characteristics of this earthquake to a certain extent. The deviation correction method for magnitude translation used in this paper can minimize the relationship between station observations and attenuation. It is a systematic deviation of the estimates, thereby reducing the uncertainty of the estimation of ground motion parameters in areas where stations are missing.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Macroseismic intensity investigation of the main events of the seismic sequence from Northern part of the Getic Depression (Romania)

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[1]*NIEP, Seismology and Lithosphere structure, Magurele, Romania*
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On February 13, 2023 a significant seismic sequence with two main earthquakes of moment magnitude M_w=4.8 and M_w=5.4, occurred in the proximity of Targu Jiu city (Romania) in the lower crust. The second shock was the largest recorded ever in this area, exceeding the magnitude of 1943 event, having an estimated magnitude of M_w 5.2 for the event occurred on June 20. The second shock was followed by hundred of aftershocks detected and located by the Romanian seismic network. Immediately after the first shock the macroseismic applications implemented by National Institute for Earth Physics (NIEP) were accessed by the observers to record their experiences regarding the felt earthquakes, information used to define the macroseismic field of ground shakings. According to the macroseismic information, the epicentral intensity reached V Mercalli for the first shock and VI Mercalli for the second one, and the seismic events were felt on the extended area (up to a distance of 300 km from the epicenter). The earthquakes caused general panic, but the buildings damages were minor to moderate only. The main purpose of this paper is to investigate the macroseismic effects associated to these earthquakes using the intensity scale in use in order to evaluate the impact on the regional seismic hazard assessment, and to improve fault characterization from the studied area.

This paper was carried out within Nucleu Program SOL4RISC, supported by MCI, project no PN23360201 and AFROS Project PN-III-P4-ID-PCE-2020-1361, supported by UEFISCDI

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Real-time forecast of long-period ground motions by Green's function obtained from seismic interferometry

DOI: 10.57757/IUGG23-2334 - LINK

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We developed a real-time forecast method for long-period (4-10 s) ground motions that appear in the distant basins when a large earthquake occurs.
The Green's functions (GFs) from the vicinity of the source to the forecast points are obtained from ambient noise interferometry, recently used by e.g. Viens et al. (2017) and Denolle et al. (2018). Since the absolute amplitude of the GFs obtained by interferometry is unknown, it is calibrated by comparing it to the earthquake waveform according to Viens and Denolle (2019).
In this study, one station in the northern Kanto, Japan was selected as the input station, and three stations in the Kanto and Nobi basins were selected as the forecast target stations. The Z-component ambient noise waveforms of the input station and the target stations were deconvolved and stacked for 1-year period to retrieve GFs. The amplitude calibration factor is calculated by comparing Fourier spectra of the forecasted and observed waveform of a Mw7 earthquake in the 4-10s period band. By convolving the obtained GFs with the input waveform of any earthquake, the long-period waveform at the target sites can be forecasted.
The method has been tested against a Fukushima-Oki earthquake (Mw7.4). The shape of forecasted waveforms and their Fourier spectra were compared to those observed at each target site and found to be in good agreement. For the practical application, application to horizontal motion of a larger earthquake, such as Tohoku-Oki Earthquake (Mw9.0), is required.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Advancements in ShakeMap-EU: Building a European seismological service through research and capacity building

DOI: 10.57757/IUGG23-3600 - LINK

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[6]*NOA, Institute of Geodynamics, Athens, Greece*
[7]*ITSAK, Engineering Seismology, Thessaloniki, Greece*
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[9]*ETH Zürich, Department of Earth Sciences ERDW, Zurich, Switzerland*

We present the status of ShakeMap-EU, an initiative initially proposed in 2018 to: (i) provide an integrated archive of ShakeMaps at the European level built on EPOS Seismology (www.epos-eu.org/tcs/seismology) services & data products and modern community software; (ii) serve as a backup to authoritative ShakeMap implementations; (iii) deliver ShakeMaps for regions where no local capability is yet available.ShakeMap-EU is accessible at the shakemapeu.ingv.it web portal since 2020, and is jointly governed by participating institutions through voluntary contributions and EC-funded projects. It has become a reliable European seismological service, integrating authoritative models and workflows consistently. The system is based on: (a) the latest version of ShakeMap®; (b) the earthquake information delivered by the EMSC (www.emsc-csem.org); (c) the earthquake shaking data distributed by ORFEUS (orfeus-eu.org/data/strong); (d) the ground motion models adopted within EFEHR (www.efehr.org) for mapping seismic hazard across Europe; (d) the official ShakeMap configurations of some of the most hazardous countries in Europe. Configuration of, and input to the system are managed via a GitHub repository that allows automatic/manual triggering and interaction by authorized users. ShakeMap-EU provides a collaboration framework and laboratory for seismological agencies to address the challenges posed by the heterogeneity of ground-shaking mapping strategies across Europe and the need to promote homogenization and best practices in this domain. ShakeMap-EU is used in research projects as the test platform for novel international collaborative research: among recent examples are the ongoing enhancements towards an evolutionary hazard information system including real-time seismicity characterization and information on earthquake-induced phenomena.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Seasonal variations of the high-frequency ground-motion site response

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Site effect assessment captures how seismic waves are amplified or attenuated on their way from bedrock depth to the surface due to the geological, geophysical and geotechnical properties of a given site. The parameter κ0 is generally utilized to describe the site attenuation at high frequencies. It is measured from the decay of amplitudes of the Fourier acceleration spectrum above the event's corner frequency. κ0 is not a simple parameter since it is influenced by e.g. the installation and housing of the sensor, high-frequency site amplification or dataset and data processing choices. This leads to a large within-station variability of the parameter.

We computed κ0 at around 200 surface-borehole station pairs of the Kik-net network in Japan and investigated its time-dependency to better understand the large within-station variability of κ0. For at least 13 sites we observe strong seasonal variations with a higher value of κ0 in winter and a lower one in summer. The difference in κ0 between summer and winter due to temperature variations is of the order of several tens of milliseconds and might therefore have an impact on the observed ground response at high frequencies.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Implications of site effect variations close to two geothermal power plants in Southwest Germany for seismic hazard assessment

DOI: 10.57757/IUGG23-3095 - LINK

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The two geothermal power plants of Insheim and Landau in the Upper Rhine Graben in Southwest Germany are located close to the village of Rohrbach. Around Rohrbach, two seismic stations monitor the induced seismicity as part of a research network. One of these stations is surface station TMO54, the other one, ROTT, a combined surface and borehole station at 300 m depth.

We used passive seismic arrays to characterize the shallow underground around Rohrbach, and evaluated seismograms to assess amplification effects. Velocity profiles were obtained by inverting the obtained Love and Rayleigh wave dispersion curves and Rayleigh wave ellipticity. Around station ROTT, we found small-scale variations of the site effects. Close to a creek, we identify a 4 m thick layer of very soft sediments with shear-wave velocity below 100 m/s, which is not present at a different investigated location at a distance of only 100 m. The V_{S30} values of these two locations are about 210 m/s and 270 m/s, respectively. For other locations around Rohrbach, V_{S30} ranges between 290 m/s and 340 m/s, where the highest value corresponds to the location of station TMO54.

The seismograms of a catalog of around 3000 induced earthquakes were analyzed to verify the amplification effects. Furthermore, the assessed site effects were incorporated to improve the deterministic estimation of ground motion for several strong events in the framework of seismic hazard assessment of induced seismicity.

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Site-specific seismic hazard assessment of sensible facilities: The importance of local seismological instrumentation

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The installation of seismic instrumentation (broadband seismometers and/or accelerometers) in the immediate vicinity of a sensitive facility (e.g., nuclear site) may be considered a significant investment, but it provides important information to improve the reliability of site-specific seismic hazard studies. Beyond the use of these data to estimate the amplification between a local reference station and a station subject to site effect (classical SSR approach), the introduction of these local records in regional or national databases allows an analysis of the soil-response of these sensitive sites with respect to more global references. In the case of a generalized inversion technique (GIT), it is possible to determine the response of the sites of interest with respect to the same reference as the one used to constrain the inversion. Similarly, in the case of a ground motion models (GMM) derivation, it is possible to analyse the dS2S terms in order to estimate the response of sites of interest relative to the median of the prediction model. This work shows the results obtained using these approaches for two sensitive industrial sites with local instrumentation implemented over a period of about ten years, located in the South-East of France (low to moderate seismicity zone). We discuss the advantages and disadvantages of these approaches with respect to other methods used in site-specific seismic hazard estimation, as well as the minimum deployment duration required.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Probabilistic seismic hazard assessment for Attica (Greece) utilizing crustal and slab seismotectonic models

DOI: 10.57757/IUGG23-0811 - LINK

George Kaviris[1], Angelos Zymvragakis[1], Pavlos Bonatis[2], Ioannis Spingos[1], Vasilis Kapetanidis[1], Spyridon Mavroulis[1], Evelina Kotsi[1], Kostas Makropoulos[1], Efthymis Lekkas[1], Nicholas Voulgaris[1]
[1]National and Kapodistrian University of Athens, Geology and Geoenvironment, Athens, Greece
[2]Aristotle University of Thessaloniki, Geophysics, Thessaloniki, Greece

In this work, seismic hazard is evaluated for the Administrative Region of Attica (Greece) and its islands. The assessment is performed by computing Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) values for return periods of 475 and 950 years for five separate groups to cover the entirety of the study area in detail. In addition, PGA hazard curves and Uniform Hazard Spectra (UHS), in terms of Spectral acceleration (Sa), are constructed for Athens and the capital of each island of Attica. The computational scheme contains two crustal seismotectonic models, i.e., the Euro–Mediterrenean Seismic Hazard Model 2013 (ESHM13) and its update ESHM20, and one slab seismotectonic model. Ground Motion Prediction Equations (GMPEs) proposed for the Greek territory are adopted and ranked for the crustal seismotectonic models. Each GMPE is re–constructed as a weight–specific model to account for both normal and non–normal fault plane solutions for each area source. The final results are obtained by implementing a logic tree, whose major branches are the three seismotectonic models and the minor branches the GMPEs. The latter reduces epistemic uncertainties due to the implementation of multiple logic tree paths per area source. The results indicated that seismic hazard is higher in groups that are close either to the Gulf of Corinth or the slab interface. The results could aid in the update of the building code in Attica.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

BhuDEV: An earthquake early warning dissemination system for Uttarakhand, India

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[1]*Indian Institute of Technology Roorkee,*
Centre of Excellence in Disaster Mitigation & Management, Roorkee, India
[2]*Indian Institute of Technology Roorkee, Department of Earth Sciences, Roorkee, India*
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The Earthquake Early Warning System Laboratory, Centre of Excellence in Disaster Mitigation & Management, Indian Institute of Technology Roorkee has developed an earthquake early warning system for Uttarakhand, a Himalayan state of the Republic of India. The Uttarakhand region is seismically active region. Large earthquakes have not occurred in this region for a long time. The return period of strong and higher magnitude earthquakes have already surpassed. So, there are likely high chances of occurrence of large earthquake in this region in the near future. The laboratory has installed ~170 sensors in the whole Uttarakhand region. They are connected through the dedicated telecommunication network. The central server is established in the laboratory. Bhukamp Disaster Early Vigilante (BhuDEV), an earthquake early warning dissemination system has been developed (here Bhukamp means earthquake). This system send the early warning on the BhuDEV mobile app and siren units installed in the Government owned buildings of the states, district emergency operation centers, state emergency operation center, schools, colleges, community centers, hospitals etc. After hearing the loud voice warnings, people can take necessary precautionary measures to save themselves and their near and dear ones. In this article, details of instrumentation, networking, processing of data and successfully issued alerts and notifications has been elaborated.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Seismic Mitigation for Ground Motion with both Long and Short Period

DOI: 10.57757/IUGG23-3185 - [LINK]

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Earthquakes have caused enormous tragedies for human beings all the time, especially in this century. A more recent tragic earthquake that has already taken four more thousand of lives is still a living tragedy nowadays in the border area between Turkey and Sialia. How to avoid this kind of tragedy becomes an important mission to almost everybody who ever works in the related field, yet the challenge is too difficult to overcome. Many approaches have been tried such as to understand the vibration source and try to predict the occurring cycle or to detect the trembling signal and try to warn the surrounding area as early as possible. All of those methods are important but not easy to approach, especially for an area that is remote, underdeveloped but populated. A more effective but cheap approach must be provided as in this research, where a typical TLCD (Tuned Liquid Column Damper) device combined with a TMD (Tuned Mass Damper) device was installed in a structure to mitigate the earthquake-induced vibrations. It is found from the results of the study that for vibrations with either a long period or short period the amplitudes of the vibration can be eased by 70% in terms of the transfer function of the displacement. According to the results in this study the method is also applicable to large and heavy buildings and structures.

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Research on high probability high frequency ground motion based on actual seismic records and source parameter uncertainty

DOI: 10.57757/IUGG23-0326 - LINK

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Shenzhen Academy of Disaster Prevention and Reduction, Shenzhen, China

The loss of earthquake disaster is mainly caused by the damage and collapse of buildings caused by ground motion, and most of civil buildings in our country are greatly affected by high-frequency ground motion. The real and accurate high-frequency ground motion is of great significance for building seismic design and earthquake damage simulation. Therefore, when evaluating the high frequency ground motion, it is particularly important to consider a variety of uncertain factors of source parameters to obtain reasonable and reliable near-field high frequency seismic motion which is more in line with the actual situation. Based on the abundant strong earthquake data and scientific research results of the Lushan earthquake, this project plans to take the Lushan earthquake affected area as the demonstration area, use the empirical Green's function method as the simulation tool. The logic tree method and statistical empirical relationship are used to comprehensively deal with various uncertainties of parameters. The non-uniform stress drop and dynamic corner frequency are introduced into the key source parameters. By establishing the sliding distribution characteristic source model considering the parameter uncertainty, the high frequency strong ground motions with higher probability of different set magnitudes are obtained. The quantifiable scheme to verify the reliability of ground motion evaluation results is tried to be given. The practical high frequency ground motion evaluation method based on real small earthquake records and parameter uncertainty is also developed. It can provide more real and reliable high frequency ground motion input for seismic design and damage simulation of buildings.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Surface seismic record estimation by borehole record correction with ambient noise

DOI: 10.57757/IUGG23-1487 - LINK

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The Korea Meteorological Administration is installing new seismic stations or replacing from surface to borehole in order to improve earthquake monitoring. A borehole station has advantage of monitoring because of reducing influence of ambient noise. However, a noticeable difference for the amplitude of the seismic record between borehole and surface seismometers because of a site effect. Thus, a surface record is necessary for calculating a seismic intensity or a structure impact assessment.
To correct the data from the borehole station, we use the amplification factor from Borcherdt (1994). This amplification factor was developed to estimate a seismic record of a surface station on a soil layer from a seismic record of a surface station on a bedrock. Applying amplification factor to the borehole record underestimates of the amplification effect. Another method is calculate the transfer function through a direct comparison of borehole and surface records. The method is that the amplification effects are well reflected as they are calculated from actual records.
In this study, We proposed a model for calculating the transfer function through direct comparing of surface and borehole records. We used 20 station that temporary surface station was installed and collect earthquake event and ambient noise data. Transfer function was calculated using ambient noise of borehole and temporary surface station. We compared temporary surface record with corrected borehole record that apply transfer function and amplification factor. As a result, borehole record corrected by transfer function was estimated more similar with surface record than corrected by the amplification factor.

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S09 - Posters - Earthquake Ground Motion and Seismic Hazard

Ground motion attenuation model for seismically highly hazardous indian zones using gradient boosting xgboost machine learning algorithm

DOI: 10.57757/IUGG23-0230 - LINK

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Our research uses a supervised machine learning algorithm (XGBoost) and strong-motion earthquake recordings from the available seismic networks in India to create a simple but powerful ground motion attenuation model for the seismically hazardous Himalayas, Indo-Gangetic plains, and Kachchh (Gujarat). Our dataset includes 564 Peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) from 145 events from 75 three-component strong-motion accelerographs in India and surrounding areas. Moment magnitudes, epicentral distances, focal depths, and Vs30 (average seismic shear-wave velocity from the surface to 30m) are our input parameters, and PGA and PSA at twenty-five periods are our output variables.

Our XGBoost model predicts ground motion using the entire dataset and a 30% randomised test dataset. Our predictability on the randomised test dataset is 0.986, and the correlation coefficient of observed and predicted PGA values for the whole dataset is 0.998. Our XGBoost ground-motion attenuation model predicts PGA and PSA datasets at four Himalayan and three Kachchh (Gujarat) stations for four events of M_w7.9, M_w6.8, M_w6.2, and M_w5.6, suggesting it would work for the Himalayas, Indo-Gangetic plains, and Kachchh (Gujarat). Another GMPE model was created using the LightGBM gradient boosting algorithm on our dataset. Finally, we compared our XGBoost model predictions to the three Himalayan GMPEs and LightGBM. The XGBoost model predicted ground motion most accurately. Period-dependent log10 output variable standard deviations range from 0.459 to 0.780. Our model predictability plots show that the current ML model can accurately predict the response spectrum for seismically high-hazard zones of India.

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Smart base-isolation systems for enhanced seismic resistance in regions prone to earthquakes: A simulation study

DOI: 10.57757/IUGG23-3086 - LINK

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The increasing frequency of seismic events highlights the need for improved seismic resistance in buildings. This study investigates the potential benefits of implementing smart base-isolation systems composed of base-isolation devices and Magneto-Rheological (MR) elastomers. The proposed system provides a semi-active solution to reduce the impact of earthquakes by adjusting its properties based on external stimuli. A smart base-isolation model was developed to simulate the behavior of MR elastomers accurately.

Numerical simulations were conducted on a five-story building subjected to various earthquake loadings, demonstrating the efficacy of the system in reducing floor accelerations and inter-story drifts during near-fault and long-duration earthquakes over a broad range of magnitudes. The simulation results suggest that the proposed system could be an effective way to enhance the seismic resistance of buildings and mitigate the damage caused by future seismic events.

The recent earthquake in Turkey and Syria, which occurred in February 2023, highlights the urgent need for developing effective seismic resistance strategies. Smart base-isolation systems could play a crucial role in enhancing the earthquake resistance of structures, potentially reducing the impact of seismic events on buildings and communities.

In conclusion, by adopting innovative and advanced technologies, we can effectively prepare for and mitigate the impact of earthquakes on our communities. Such proactive measures are crucial in ensuring the safety and resilience of our built environment in the face of inevitable natural disasters.

Keywords: earthquake-resistant building, smart base-isolation, MR elastomers, numerical study, seismic performance, semi-active system.

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Reconstructing ground motion from past earthquakes in the Vrancea Seismic Zone using ambient seismic noise

DOI: 10.57757/IUGG23-4077 - LINK

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The Vrancea Seismic Zone (VSZ), located in Romania, at the sharp bend of the South-East Carpathians, is an anomalous intra-plate seismic nest releasing the largest strain in continental Europe. The last powerful earthquake in Vrancea occurred in 1977 causing significant damage to the densely populated cities in South-East Romania. The seismic infrastructure was underdeveloped at that time and the earthquake was not well-recorded locally. Using ambient seismic noise recorded at modern broadband seismic stations around Vrancea in the year 2020, and the approximate moment tensor solutions of historical earthquakes Mw>6 since 1977, we reconstruct ground motion waveforms recorded by modern seismometers decades after their occurrence. The Virtual Earthquake Approach uses empirical Green's functions from ambient noise cross-correlations between pairs of seismic stations and adds the signatures of a model earthquake: double couple mechanism, buried source and a realistic earth model in the epicentral area. Ambient noise data capture the signatures of complex subsurface structures and the 3D path effects, providing a more physically accurate representation of the seismic wavefield than purely synthetic data. Our new results demonstrate the viability of this innovative method and provide a unique opportunity for more accurate seismic hazard analysis in intra-plate seismic zones with insufficient historical data.

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Perturbations of free-field seismic recordings caused by coupling slabs, short wavelength topography and soil-structure interaction: Preliminary results from empirical studies

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Recording ground motions is essential to estimate the seismic hazard. Signals from the databases are often considered to be in free-field, i.e. at the natural surface of the ground, without disturbances due to buildings or neighbouring structures. Nevertheless, the analysis of seismological networks has highlighted many installation modalities, including the coupling of seismometers, coexist. Recent studies have also shown that the installation conditions of these seismological stations can have a significant impact on the recorded motion, compared to true free-field measurements. Similarly, the effects of topography on a metric or decametric scale are poorly studied but also impact on the measurement at high frequency.

This study focuses on a qualification of the effects of installation of seismometers, through several experiments that have been set up in Greece, mainly in Cephalonia Island, chosen for its high seismicity. The influence of the coupling methods of the seismometers is studied using the experiment called "ArgoSlab", where around thirty seismometers have been installed on slab or on seismic pillar of different size and shape, outdoor or sheltered, and compared to the recordings obtained by free-field sensors. The effect of topography at the metric and decametric scale is addressed by the analysis of about fifteen seismometers installed in the hill of Krani, near Argostoli (« ArgoScarp » experiment). Finally, the analysis of soil-structure interaction is carried out by the comparison of sets of sensors in free-field (several tens of metres from the building), very close to buildings and inside buildings (basement and top floor).

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The 21 November 2022, Mw 5.6 Cianjur earthquake: aftershock, intensity, and peak ground acceleration

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A moderate earthquake struck the Cianjur Regency, in West Java, Indonesia, On 21 November 2022 at 13:21 local time, the hypocenter is 6.86°S 107.01°E depth of 11.0 km, with moment magnitude Mw 5.6 with an epicenter located about 100 km Southeast Jakarta, this event is possibly related to Cimandiri fault system. The mainshock also followed by a landslide in Cugenang District. This moderate earthquake causing extensive damage, great economic loss and casualties especially in the Rawa Cina, Cugenang, Warung Kondang and surrounding regions. The focal mechanism is dextral strike-slip fault, the faulting orientation of the mainshock was strike = 347°, dip = 83, the strike direction still controversy. In this research we want to find scientific proof of the true strike direction using aftershock analysis. The mainshock was followed by aftershocks productivity may due to complex faulting systems and relatively heterogeneous stress state in that region. We deployed 6 portable seismographs and analyzed aftershock distribution join with data of the permanent seismograph network (InaTEWS Network). The result shows that aftershock tend to distribute in the North-East direction. We also compute Peak Ground Acceleration (PGA) based on the event, Peak Ground Acceleration is 290 gal. It is relatively high acceleration of magnitude 5.6 may because of volcanic sediment amplify the ground shaking.

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Rapid methods for the estimation of the topographic amplification and consideration in site-specific response spectra.

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Topographic effects result from the influence of the surface geometry on the seismic ground motion and may generate strong amplifications, generally at hilltops and crests. They have caused significant damage during past earthquakes. They must therefore be accurately estimated even in areas of moderate seismicity. Despite numerous studies conducted over the last fifty years (Massa et al., 2014), the main parameters responsible for this phenomenon are not all identified, notably because of the difficulty in differentiating in recordings the effects of the surface geometry from others such as lithological site effects due to subsurface heterogeneities, faults, fractures and so on. Furthermore, topographic effects are mentioned in the Eurocodes8 in the form of simplified coefficients, independent of the frequency and subjected to interpretation. Therefore, topographical effects are rarely taken into account when generating site-specific response spectra. Thus, we propose to compare alternative approaches based on simple and easily accessible parameters. They are: - the FSC method developed by Maufroy et al. (2015) and - SuperTau method developed by the BRGM based on the previous French seismic regulation (PS92). Here, we firstly compare the estimations of topographical amplification computed by both methods for two case studies: the district of Menton in the south of France and the Dembeni site on the island of Mayotte. In a second step, we discuss how to consider topographic effects at these two sites in the associated response spectra.

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Assessing the seismic hazard of the Campotosto Lake dams by near-source ground motion simulations

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We apply the Probabilistic Seismic Hazard Analysis (PSHA) and Physics-Based Simulations (PBS) to compute the ground motion for three dams in the Campotosto area (Central Italy). The dams, which confine an artificial water reservoir feeding hydroelectric power plants, are located in an active seismic zone between the areas that experienced the 2009 L'Aquila and 2016–2017 Central Italy seismic sequences. The probabilistic disaggregation estimated for a return period of 2475 years, corresponding to the collapse limit state for critical facilities, indicates that the most dangerous fault is associated with a maximum magnitude of 6.75±0.25 within a distance of 10 km. This fault is used in PBS to emulate the Maximum Credible Earthquake scenario. To capture the ground motion variability, we input a pseudo-dynamic source model to encompass spatial and temporal variations in the slip, rise time and rupture propagation, heavily affecting the near-source ground motion. Indeed, the ground motion above the rupture volume is mainly influenced by the epistemic uncertainties of rupture nucleation and slip distribution. The computed broadband seismograms are consistent with the near-source shaking recorded during the 2016 M_W 6.6 Norcia earthquake and constrain the upper bound of the simulated ground motion at specific sites. Our modelling reinforces the importance of considering vertical ground motion near the source in seismic design. It could reach shaking values comparable to or larger than those of the horizontal components. This approach can be applied in other areas with high seismic hazard to evaluate the seismic safety of existing critical facilities.

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Region Specific Ground-motion Prediction Equations for Small to Moderate Shallow Crustal Seismicity in Uttarakhand Himalaya

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Ground-motion prediction equations (GMPEs) are a reliable and fast means to predict strong ground motions. They play a crucial role in estimating seismic hazards levels for any region using either deterministic or probabilistic approaches. Due to the scarcity of ground motion data, GMPEs are assumed ergodic and are borrowed from the host region and adapted/adjusted to target regions which results in large aleatory variabilities. Development of regional GMPEs is challenging because it requires a lot of data to constrain the uncertainties, which are not always available. Therefore, we developed region specific GMPEs for shallow crustal earthquakes in western Himalayan region. We used data from 80 earthquakes in the magnitude (M_L) range of 3 and 5.5 recorded at 27 strong motion seismic stations. The hypocentral distance range varies between 5km and 262km. We developed GMPEs for PGV, PGA and PGD values employing a non-linear mixed effect regression. We developed the reference model by initially considering the source and medium effects and subsequently incorporate the Vs-30 values to account for the local site effects and obtain the final model. It is emphasized that the model is able to explain the observations even with limited number of parameters without making the equation too complex, which otherwise becomes difficult for engineers to implement while evaluating seismic hazard. The residual values at each station are analyzed to quantify the role of epistemic uncertainties. The inter-event and intra-event residuals are also analyzed with respect to magnitude and distance.

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Site specific seismic Hazard analysis for central Alborz basin

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The Alborz mountain range is part of the Alpine–Himalayan seismic belt that passes through northern Iran and considers as an active region within the Arabia–Eurasia collision zone. The southern part of central Alborz is the most populous regions in Iran, home to over 15 million people. The central Alborz basin is located between longitudes 50.5°E and 51.5°E, and includes the cities of Tehran and Karaj, as well as approximately 50 smaller developing towns. While the empirical site amplification from temporary seismological network deployed in the region revealed significant ground motion amplification over a broad frequency range from 0.3 Hz to 4 Hz in Tehran, amplification in Karaj is moderate. Recently, Soltani et al. (2023) derived a 3D velocity model of the Tehran's basin using active and passive surface waves methods. This velocity model exhibit a very thick sedimentary cover on the southern part of the Tehran basin with a seismic bedrock depth around 900 m, consistently with a fundamental resonance frequency of about 0.4 Hz. In this study the same peak observed in the southern part of Karaj shows the possibility of deep alluvium structure in this area and suburb towns. We extend the existing model to the west and south in order to develop the first site specific hazard map in central Alborz. With total amount of data include 19 temporary seismic, 800 single station measurements, 38 passive and over 50 active array measurements we also develop the first 3D shear wave velocity for central Alborz basin.

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A Python algorithm for ensemble initialization and reduction in urgent computing applications and probabilistic shakemaps retrieval

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We present our contribution to the UCIS4EQ (Urgent Computing Integrated Services for EarthQuakes) workflow, where multiple realizations of ground motion fields are required to account for input and model uncertainties under emergency conditions. Our focus is on the initialization and update of an ensemble of scenarios describing the seismic source uncertainty for Urgent Computing (UC) applications.

We propose an algorithm to reduce the size of the ensemble for UC usability, such that source uncertainty can be propagated to shaking with numerical simulations of a subset of seismic sources while preserving the key statistical properties of the full ensemble. As target distribution representing the expected shaking variability in the earthquake-hit area, we use the distribution of PGA (Peak Ground Acceleration) values predicted by local GMPEs (Ground Motion Prediction Equations) for the seismic scenarios in the full ensemble. Besides accounting for source uncertainty, our approach estimates the uncertainty associated with the ensemble sampling method and available GMPEs. By sampling an increasing number of seismic scenarios from the full ensemble, the algorithm estimates the total variability of the subsample and assesses its convergence to the target distribution.

Besides reducing the time and cost of shaking scenarios simulations, it also enables the retrieval of probabilistic shakemaps, an evolved version of the traditional shakemaps where each POI (Point Of Interest) is assigned a probability distribution of PGA values quantifying both the source and GMPEs uncertainty.

Our algorithm is written in Python and makes use of OpenQuake and Shakemap libraries.

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A vulnerability-based method for the selection of ground motion models for probabilistic seismic hazard analysis

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Ground motion models (GMMs) are one of the fundamental ingredients of probabilistic seismic hazard analysis (PSHA). Usually, to capture epistemic uncertainties, alternative GMMs are adopted in PSHA applications and merged using the traditional logic tree/ensemble approach. In such approach, each GMM needs a weight that reflects its relative importance. Data-driven methods suggest using weights based on the performance of GMMs against actual observations (i.e. ground motion recordings). The classical score used for this performance evaluation is the average sample log-likelihood (LLH). LLH is defined as the average log-likelihood score of the GMM against observations. In this work, we introduce a method to move from the classical average to a weighted average, i.e., an average where the weights are not equal to 1/N (where N is the total number of observations). We based our weighted average on fragility functions, to assign the performance of the GMM according to the target infrastructure type that will be the subject of the PSHA (e.g., masonry buildings, earth dams, bridges, levees). We compared the proposed approach with the classical LLH using instrumental data from Central Italy. Finally, we discussed the advantage and drawbacks of our approach in PSHA applications and outcomes. Applying this novel approach provides different values of the relative importance of each analysed GMM and changes ranking positions in a meaningful and repeatable manner.

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A forecast of long-period ground motions by using a convolutional neural network

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In this study, we propose a CNN based forecast model for long-period (2-10 s) ground motions that occur in large basins of populated cities in large earthquakes.

The CNN model consists of seven convolutional layers with ReLU activation functions, which are flattened and finally fed to a fully connected layer. The forecast takes as input the 5-min waveforms of two horizontal components at five stations near the epicenter and outputs a velocity response spectrum for periods between 0.1 to 100 s. 56 inland earthquakes with Mw>4.5 and 5 earthquakes with Mw>6 that occurred in central Japan during 2004-2010 were used as training data. To compensate for the lack of larger events, 3D-FDM simulation of seismic waves for Mw>6 earthquakes were conducted. Using these training datasets, the CNN was trained for 50 epochs.

Using the trained model, we examined the forecast performance for 11 earthquakes with Mw>4.5 occurred in the same area during 2011-2022. The model performance is evaluated by the average of the ratio of the sum of forecasted spectrum to observed values over period of 1 to 10 seconds. The result shows a good performance (0.9-1.2) except for the largest earthquake (Mw6.7), which was out of the data set. This problem was solved by adding numerical simulated waveforms for large earthquakes to the training dataset, which improved forecast performance for all events, including Mw6.7. Hybrid learning using observation and simulation data is considered to be an effective technique to compensate for the small amount of large earthquake data.

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Analysis of moderate and large magnitude ground motions in Turkey: Evidence of azimuthal variations associated with directivity effects

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Turkey is home to two major fault systems, which make it the most seismically active country in Europe. These are namely the right-lateral North Anatolian Fault (NAF) and left-lateral East-Anatolian Fault Systems (EAF) with lengths of á ~1500 km and ~500 km, respectively. They are capable of producing moderate to large earthquakes in given time periods. Starting from the most western point, on 26 September 2019, a sequence of moderate-sized events (Mw 5.8; Mw 4.1 and Mw 4.7) occured on the Main Marmara Fault (westernmost branch of NAFZ). Only 3 years later the central part of the NAF produced (after a silence of 23 years) a Mw 6.0 earthquake close to Düzce province (Gölyaka Earthquake), the region that was hit in 1999 by an Mw 7.2 event that killed more than 700 people. Most recently, the EAF ruptured in three different segments and generated two large earthquakes just within a time-span of 9 hours: Mw 7.8 (Pazarcik Earthquake) and Mw 7.7 (Elbistan Earthquake). The events have killed so far over 45,000 people and are the most destructive earthquakes with the highest death toll in modern times. Based on the dense Turkish seismic network (AFAD-TADAS), we analyze the strong ground motions in terms of their spatial variation and realize azimuthal variations in peak-ground acceleration (PGA) and peak-ground velocity (PGV) with regard to rupture propagation, coupled with evidence of strong velocity pulses. This trend has been interpreted as directivity effects which systematically occur on sites located towards rupture propagation.

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Reduction method of liquefaction damage using grouting applicable to existing structures

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Soil liquefaction is causing great damage to the structure during earthquake. Many soil liquefaction damage reduction methods have limitations in their application to existing structures. Therefore, in this study, a 1-G Shaking table test was performed, a soil liquefaction damage reduction method applicable to existing structures was studied using the grouting method. The effect of reducing structural damage was analyzed according to various grouting mixing ratios, and the separation distance between the grouting chemical injection point and the structure. As a result of the analysis, when the ground was reinforced by applying the grouting method, the structure settlement was smaller than when the ground was not reinforced, and the mixing ratio with the smallest settlement was 0.45. In addition, when there was no separation distance between the structure and the grouting chemical injection point, it was confirmed that the effect of reducing structural damage was the greatest. This study will be used as basic data for the development of grouting methods applicable to existing structures..

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S10 - Posters - Multi-Hazard Risk Assessment

Multi-hazard insurance premium rate-making using earthquake-tsunami risk model for the district of Tofino, British Columbia, Canada

DOI: 10.57757/IUGG23-0237 - LINK

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Canada has a high likelihood of facing significant earthquake threats in the future. On the Pacific coast, southwestern British Columbia is exposed to significant seismic and tsunami hazards, originating from the Cascadia subduction zone. A scenario of particular concern to residents and emergency managers is the future occurrence of a moment magnitude (M) 9.0-class megathrust earthquake in Cascadia. The scientific challenges in assessing the potential hazards and risks for residents and assets in British Columbia include the characterization of the earthquake rupture of future major Cascadia events and the modeling of their multi-hazard cascades which affect the population and built environment simultaneously. To protect households from potential financial risks due to the Cascadia events via insurance, it is necessary to quantify the monetary losses from ground shaking and tsunami. However, such multi-hazard risk assessments have not be carried out to determine insurance premiums. This study presents a probabilistic earthquake-tsunami loss model for the Cascadia subduction zone by focusing on the District of Tofino, British Columbia. The earthquake occurrence and rupture models for the Cascadia subduction zone are developed by incorporating the time-dependency of earthquake occurrence and by adopting a stochastic source modeling approach, which allows considering heterogeneous earthquake slip distributions. The results produce single-hazard and multi-hazard exceedance probability loss curves for strong motions and tsunamis. These loss curves can be used for determining the insurance rates for the multi-hazard risk coverage for Tofino. The results are beneficial for providing more risk financing options via insurance against the future Cascadia events.

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Tofino. The results are beneficial for providing more risk financing options via insurance against the future Cascadia events.

Seismic potential of Main Recent Fault (Iran): Insights from interseismic fault locking, slip rate, and earthquake recurrence interval

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State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu, China

The Main Recent Fault (MRF) is an important boundary fault that accommodates the oblique convergence motion between the Arabian and Eurasian plates. Several large earthquakes including the 1909 mb 7.4, 1958-1963 three events with magnitude larger than Mw 6.0, and the 2006 Mw 6.1 earthquake had ruptured the central segment of MRF. However, there is no large earthquakes occurred in the northwest segment in the past hundred years. In this study, the interseismic surface deformation along the northwest segment of the MRF has been firstly mapped from the Synthetic Aperture Radar (SAR) images observed by the Sentinel-1 satellite. Then, the ununiformed fault slip rate, locking and deficit are estimated based on the measured interseismic surface deformation. The results show that the fault slip rate varies from 1.0 mm/yr to 4.0 mm/yr in the northwest segment of MRF. In addition, the fault locking pattern is very complex in this segment, and 13 sub-segments could be divided based on the fault locking distribution and historical earthquakes. A seismicity gab is identified from the historical earthquakes, which has a good space consistency with the transition between the significant shallow locking and deep free creeping zones. According to the potential seismic magnitude and estimated recurrence interval, it is found that five segments are approaching the end of their interseismic recurrence interval.

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Effect mechanism of earthquake-induced landslide surge on collapse resistance of RC bridge structure

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In order to determine the collapse mechanism of seismic landslide surge induced bridge structure, this paper takes reinforced concrete bridge as the research object, an analytical calculation model of surge wave considering the impact characteristics of sliding body on fluid was established; on this basis, the influence law of sliding body velocity of entry into the water on surge propagation is analyzed, the wave pressure distribution law of landslide surge along RC bridge structure is studied, the plastic hinge development sequence of RC bridge structure under landslide surge is determined, and the influence mechanism of earthquake landslide surge on the anti-collapse performance of bridge structure is revealed. The findings show that considering the impact force of sliding body on water, the velocity of entry into the water has great influence on the wave height and the height climbing on RC bridge structure, but has no obvious influence on the shape of the surge wave; the influence of surge on RC bridge structure is related to the initial wave height, and the influence degree of surge on bridge structure increases with the increase of the first wave height; the vertical wave force caused by landslide surge could not be ignored, which will lead to the change of the emergence time of different plastic hinges in RC bridge structure, and in the anti-collapse analysis of RC bridge structure, the formation of all plastic hinges of RC bridge cannot only be taken as the discriminant index, but the ultimate curvature of each plastic hinge should be combined to judge.

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S10 - Posters - Multi-Hazard Risk Assessment

An analysis of elements at risk using weight of evidence method for seismically induced landslide susceptibility

DOI: 10.57757/IUGG23-0549 - LINK

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Landslide is the most prominent and frequently occurring geophysical phenomenon in the Northern and Northwestern region of Pakistan and Azad Jammu & Kashmir. The landslides are not only induced by topographic and environmental factors, but the seismically induced events are frequently experienced. This research uses the technique on theorem of Bayer's bivariate statistics (weight of evidence) which predicts the events geographically using the input layers and the relationship of event. The use of Landsat (30m) data along with the integration of statistical method is an effective tool in predicting the landslide prone areas. A statistical relationship between event of landslide and factors was studied and analyzed using this method. Subsequently a prediction of the occurrence of the spatial location of the landslide event was established successfully. The relationship of distribution of landslide and factors layers was calculated using the statistical methods which enabled to predict the landslides zones in different areas. The methodology adopted resulted in success rate of 80% indicating that the landslide events occurred in 18% area with the prediction rate of 70% using Area under Cover (AUC). The result of the assessment will be integrated into exposure and risk analysis for landslide taking population, infrastructure and other key elements at risk for determining a holistic risk picture of the study area.

Keywords:

Bayer's Bivariate Statistics, Weight of Evidence, Seismically Induced, Landslide Susceptibility, Area under Cover (AUC), Elements at Risk, Exposure and Risk Assessment

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Keywords:

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S11 - Posters - Site Response in Urban Areas

Seismological studies for site effect characterization of Ancona city following the Mw 5.5 Costa Marchigiana-Pesarese earthquake (Central Italy)

DOI: 10.57757/IUGG23-4187 - LINK

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We present the activities of EMERSITO, the INGV emergency task force with skills and experience in seismic response studies and in seismic microzonation, in the follow-up to the Mw 5.5 (ML 5.7) earthquake of November 9, 2022 06:07:25 UTC localized in the Costa Marchigiana Pesarese area (Central Italy).

Based on geological information and damage estimates in the epicentral areas, EMERSITO focused its intervention in Ancona, the capital of Regione Marche, located at about 40 km south of the epicenter. This city is located in an area characterized by a remarkable seismic hazard, as evidenced by the extensive damage of the 1972 earthquakes (Mw up to 4.7), with part of the urban territory susceptible to landslide phenomena.

A temporary seismic network consisting of 11 seismic stations equipped with velocimeter and accelerometer was installed in different urban areas of the city, acquiring data in continuous mode for about 4 months. The analysis of ambient vibrations and aftershock recordings collected by the network suggests a variability of the site response depending on the outcropping lithologies. The peak frequencies from spectral ratio analysis range between 1 and 3 Hz for 6 stations, while other stations are characterized by peak frequencies between 3.5 and 9.5 Hz. The H/V noise spectral ratios do not show peaks with very high amplitudes (< 3), likely indicating the lack of strong impedance contrasts, at least in the shallow part of the subsoil.

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S11 - Posters - Site Response in Urban Areas

Performance of different ANNs on microtremor H/V peak classification

DOI: 10.57757/IUGG23-4665 - LINK

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Recent applications of ANN, in geophysics include, e.g., the prediction of site amplification response (Boudghene Stambouli et al. 2017; Salameh et al. 2017; Bergamo et al. 2021) and seismic site classification (Zhao et al. 2006; Ghasemi et al. 2009; Ji et al. 2021; Díaz et al. 2022).

The identification of significant peaks on microtremor H/V curves is traditionally assessed by means of the popular SESAME (2004) criteria, which, however, cannot discriminate between the stratigraphic and non-stratigraphic nature of them.

Non-stratigraphic peaks are typically caused by machineries acting in the proximity of the recording station or result as an effect of vibrations induced from large nearby structures. Low frequency artefacts perturb the noise wavefield up to large distances from the source.

The frequency of anthropogenic peak can also coincide or be very close to the frequency of a peak of stratigraphic origin. H/V curves are easily affected by artefacts that it is mandatory to discriminate them, before attempting any interpretation of the H/V curve itself.

Given the worldwide extended use of H/V methods in seismic microzonation, being altered about the possible presence of non-stratigraphic peaks is important to avoid misclassifications of soil resonance frequencies or wrong stratigraphic interpretations when the H/V method is combined with, e.g., surface wave multichannel methods to achieve Vs profiles. Given the limited capability of standard techniques in this type of signal classification, we decided to explore the performance of different NNs in this sorting problem consisting in discriminating between stratigraphic and non-stratigraphic features in microtremor signals.

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S11 - Posters - Site Response in Urban Areas

Vs30 and depth to bedrock estimates using H/V measurements and geology and slope approach in the Oslo area, Norway

DOI: 10.57757/IUGG23-2718 - LINK

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[2]*University of Oslo, Geosciences, Oslo, Norway*
[3]*The Arctic University of Norway, Geosciences, Tromsø, Norway*

Common practice to perform a seismic hazard study at regional scale is to present the results computed at bedrock condition. Site effects are usually not considered because soil information is not always available. Our goal is to carry out a site-specific seismic hazard study for the city of Oslo (Norway), conducting a microzonation study that will include site effects. More specifically, the average shear wave velocity in the upper 30 meters of the ground (Vs30) has been introduced to become the main attribute to characterize the soil type and subsequently account for soil type related seismic amplification

Vs30 values are missing for the Oslo area, therefore we propose an integrated approach that estimates Vs30 using Horizontal-to-Vertical Spectral Ratio (HVSR) method together with a combined geology-slope approach. A campaign with 61 H/V measurements has been performed between March and June 2021 at specific locations in Oslo. Topographic slope attributed are extracted from DTM10 (10 m horizontal-scale resolution Digital Terrain Model), provided by the Norwegian Mapping Authority agency. In addition to resulting Vs30 values, this method will also allow us to define depth to bedrock estimates, which will likely be required for an updated Eurocode. This procedure is applied in specific areas in the Oslo urban environment that are susceptible to site effect amplifications.

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Local seismic response for highly risk-exposed urban areas

DOI: 10.57757/IUGG23-1688 - LINK

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The paper investigates the seismic response of highly populated, or economically important areas for a wide range of magnitudes. Intermediate-depth earthquakes occurring in Vrancea, Romania, are the most hazardous seismic source at national scale, affecting large parts of the country territory.

The sites are representatively chosen for their different local soil conditions given by the specific rocks content, layering and impedance contrast in the shear waves velocity. The response at each site is investigated through spectral composition by comparing the processed elastic response spectra of strong earthquakes to those of medium or smaller magnitude. For this reason pairs of collocated (depth, hypocentral distance) stronger-lower magnitude are chosen, in order to minimize the effect of propagation path. The local amplification in correspondence to the site characteristics is highlighted and spectral ratios for each of the pairs of elastic response spectra were performed, in order to correlate the specific site's behavior to the local effects as influenced by the seismic source strength.

The influence of local conditions is enhanced by the increase in magnitude, as higher magnitudes probably set in motion thicker package layers, and an increase in the soil predominant period values may be encountered. For some other areas the oscillating period corresponding to the peak spectral amplitude is rather stable, hence the local site conditions are primarily controlling this behavior. The stabilization tendency for the spectral content offers the possibility to predict the characteristic values even for the future strong seismic events in these areas.

Work financed by Nucleu PN2336 SOL4RISC

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Site effect study at the foot of the Mount Cameroun volcano in Buea city

DOI: 10.57757/IUGG23-4593 - LINK

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CRGV Centre for Geophysical and Volcalogical Research, Yaounde, Cameroon

Mount Cameroon is an active volcano located at the junction of the continental and oceanic part of the Cameroon Volcanic Line and has so far experienced effusive, explosive and hydromagmatic type eruptions. During the last century, it experienced 7 major volcanic eruptions, including the March-April 1999 eruption. Interring in its premonitory phase, it released a series of precursor earthquakes, one of which occurred on March 28 at 8:12 PM with a moment magnitude of only 5.1. Against all odds, this earthquake caused very significant damage in certain buildings in Buea, a city located at the foot of the volcano. The fact that a building by its typology and the nature of its materials has a natural frequency which when it is on a ground vibrating at equal frequency will get into resonance, bring us to think that it is possible to face here a phenomenon of site effects. In this work, we bring a beginning of explanations to this unequal distribution of the damage observed in the buildings of the city of Buea. Using the ambient noise recordings carried out between January 2005 and February 2007 by the stations of the project ''Cameroon Broadband Seismic Experiment'' in the area of Mount Cameroon and its surroundings we proceeded to the computation of the horizontal to vertical spectra ratio. This reveals that seismic waves are amplified at some specific frequencies.

Keywords: Mount Cameroon, site effects, HVSR, ambient noise and seismic waves.

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Are the homogenous micro-zones really homogeneous from a seismic response point of view?

DOI: 10.57757/IUGG23-3412 - LINK

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The seismic shaking of an area is strongly affected by the local geological stratigraphy (e.g., the presence of soft soils overlaying a rocky bedrock). The so-called local site effects are deeply investigated in literature and must be considered for the estimation of seismic effects on structures and urban planning. Thus, the Seismic Microzonation (SM), is the process aimed at identifying and mapping, usually at urban/municipality scale and in terms of ground shaking parameters and susceptibility to ground instabilities, the subsoil local response in a given area. The Italian Guidelines for Seismic Microzoning have been in used in Italy since 2008. According to these guidelines a modular approach that identify three levels of details is proposed. The aim of the level is to identify areas characterized by the same seismic response. These areas are called homogenous micro-zones in the seismic perspective and are defined on the basis of available data, new geological/geomorphological surveys, and low-cost geophysical measurements. These homogenous micro-zones in the seismic perspective are expected to have the same resonance frequency and to amplify the seismic input more or less in the same way. In this work the results of a single station seismic noise campaign carried out in the city of Trieste (Italy) are presented. Thirty three measurements, analysed according to the horizontal to vertical spectral ratio (H/V) techniques, were carried out over four different homogenous micro-zones in the seismic perspective. Results show that the hypothesis of homogenous micro-zone in the seismic perspective is not always verified.

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S11 - Posters - Site Response in Urban Areas

Evaluating the applicability of the microzonation simplified approach (national abacuses) in the plain of the Friuli Venezia Giulia Region (Italy)

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The seismic shaking of an area is strongly affected by the local geological. The so-called local site effects must be considered for the estimation of seismic effects on structures and urban planning. Thus, the Seismic Microzonation (SM), is the process aimed at identifying and mapping, usually at urban/municipality scale and in terms of ground shaking parameters and susceptibility to ground instabilities, the subsoil local response in a given area. The Guidelines for Seismic Microzoning (SM) have been in used in Italy since 2008. According to them a modular approach that identify three levels of details is proposed. The second level aims at quantify the seismic amplification (Amplification Factor, AF) of the different homogenous micro-zones in the seismic perspective (identified in the SM first level) and eventually re-shape these areas. To do that a simplified approach (tables of correspondences called seismic abacuses and available for the whole national territory) is proposed for areas that can be schematised thanks to a 1D subsoil model (e.g., alluvial plain). In this work the results of the comparison between the AF values retrieved from national abacuses applied in the Friuli Venezia Giulia (Italy) plain municipalities and those from numerical simulations are presented. In general, AFs from abacus are lower excepted for the area of Pordenone municipality or some isolated sites. Moreover, the response spectra derived applying the AF values (both from abacuses and numerical simulations) have been compared to those proposed by the Italian Building regulation. These last in most cases underestimate the soil effects.

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Estimation of Shallow S-wave Velocity Structures in the Kathmandu Valley, Nepal, using Microtremor Array Observation

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The Kathmandu Valley is filled with soft lake sediments with a thickness of more than 650 m in the central part. The thicknesses of these sediments vary a lot in the valley. The site amplification characteristics of this sedimentary structure resulted in significant damage during past large earthquakes. During the 2015 Gorkha, Nepal earthquake (M_w 7.8, 8.2 km), the observed damage was concentrated in a few areas which can be considered as a function of the local site effect. Constructing the shallow to deep sedimentary velocity model is important to reduce damage by future earthquakes. Strong motion seismometers have been installed at 14 sites in the Kathmandu Valley. The deep velocity structures under these stations have been discussed with strong ground motion records. In this study, we explored 18 sites using small-sized equilateral triangle microtremor arrays at the strong motion stations and in the damage-concentrated area of the 2015 Gorkha earthquake to understand the shallow S-wave velocity structure. We applied the spatial autocorrelation method to the observed microtremor records and obtained the phase velocities of the Rayleigh wave between 5 to 30 Hz. The phase velocities in the high-frequency range differ at sites on bedrock, lacustrine sediments, and fluvial sediments. We inverted S-wave velocities from these phase velocities dispersion curves using genetic algorithms. The average S-wave velocities of the upper 30 m of each site calculated from the estimated velocity structures are 130-400 m/s and correspond with geological formation classification.

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S11 - Posters - Site Response in Urban Areas

Passive and active seismic surveys for site investigation in Bucharest using seismographs dense array: preliminary results

DOI: 10.57757/IUGG23-4008 - LINK

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This work presents a preliminary study focused on a site characterization conducted in the Bucharest area using a dense temporary seismic array. The aim is to obtain a more in-depth understanding of the subsurface velocity structure at the location of a seismic station that is a part of the Romanian Seismic Network (RSN), and located in the wider central region of Bucharest, at Cutitul de Argint. The seismic data were collected using 15 newly released Atom-3C wireless seismographs. The Atom-3C seismograph is a turnkey solution for assessing subsurface conditions, much quicker than traditional land seismic surveys, requiring no spread cables. It has separate acquisition units with 24-bit A/D conversion, GPS-controlled timing, 4 GB of internal data storage, a configurable sample rate and batteries that can last up to 70 hours before they need to be recharged. The seismic surveys were performed adopting different array geometries, such as an L-shaped array for microtremor array measurements (MAM) and a linear array for multichannel analysis of surface waves (MASW). We show some preliminary results in terms of the shear wave velocity (Vs) structure for each active and passive survey, and for the combination of active and passive survey data along the linear configuration of the array.

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S11 - Posters - Site Response in Urban Areas

The subsoil of the city of Rome (Italy): Results from a dense temporary seismic network

DOI: 10.57757/IUGG23-2955 - LINK

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We present the results from a temporary seismic network of 24 stations installed in the urban area of Rome (Italy) from January 10, 2021 until April 08, 2021, with the aim of studying the city's urban subsoil through analysis based on ambient seismic noise.

Rome is the largest Italian city (with about three million people) with a history of art, architecture and culture that influenced the world and dating back almost 3000 years ago. The city retains a monumental heritage characterized by a high fragility due to its age. Both the high number of inhabitants and the fragility of its monuments make the city particularly vulnerable to possible earthquakes, even if the seismic hazard of the area is considered as moderate.

The continuous recordings from the network allowed the use of ambient seismic noise to derive spectral ratios at sites located in different geological and lithological contexts. Moreover, signals from regional earthquakes were surprisingly well recorded despite the high anthropic noise-level, showing a clear areal variability referable to site effects. In this case, we also benefit from a low-noise period due to the partial lockdown for COVID pandemia. Interferometric analyses based on seismic noise cross-correlation of acquired data, show that it is possible to reconstruct the surface waves at station pairs in the frequency band between 0.2 and 1 Hz. It is then possible to perform a 3D velocity model through Ambient Noise Tomography to characterize shapes, thickness and properties of different geological/lithological units of the subsoil of the city.

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S11 - Posters - Site Response in Urban Areas

Horizontal-to-vertical spectral ratio at four major cities of KwaZulu-Natal

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Brian Zulu[1], *Brassnavy Manzunzu*[1], *Thifhelimbilu Mulabisana*[1], *Tebogo Pule*[1], *Lucky Semelane*[1], *Thandeka Zulu*[1], *Kamogelo Sydney Khumalo*[1], *Vunganai Midzi*[1]
[1]*Council for Geoscience, Engineering and Geo-hazards, Pretoria, South Africa*

Site effects associated with local geological conditions constitute an important part of any seismic hazard assessment. The horizontal-to-vertical spectral ratio (HVSR or H/V) was carried out in pre-selected major KZN cities, including: Pietermaritzburg (PMB), Port Shepstone (PS), Richards Bay (RB) and St Lucia (SL). A total of 159 sites across all four cities were surveyed. The data collection was in line with the recommendations of the Site Effects assessment using Ambient Excitations (SESAME) by the European Commission 2004. The Tromino 3G instrument was placed on the ground facing the North direction at all sites. The sampling frequency was set at f = 128 Hz. The recording duration was set at 30 minutes to be able to record a minimum expected fundamental frequency (f_0) of 0.5 Hz. The collected data was processed using a software called Grilla for a window length of 30 minutes, window size of 20 seconds, a Triangular window smoothing type and 5% sampling frequency rate of 128 Hz. The H/V response curves were obtained for each site. The H/V response curves obtained were used to estimate the predominant frequency and peak amplitude (lower bound approximation of site amplification) for each site. The spatial distribution of obtained predominant frequencies for sites close to soft sediments (closed to the sea) were generally higher compared to those inland (rocky areas). The predominant frequency was classified to 5 identified classes which varied although majority of the sites are between 0.5 Hz and 50 Hz across all cities.

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S12 - Posters - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Using GNSS PPP to image surface displacement: application to the 2023 Turkey earthquake sequence

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GNSS observations are available at a high temporal frequency and accuracy. Their usefulness in capturing coseismic deformation during large earthquakes is here tested. Precise point positioning (PPP) is used to compute coordinate time series for 61 stations of the TUSAGA-Aktif network during the 2023 earthquake sequence. Precise GPS, GLONASS and Galileo satellite orbits and clock offsets computed by GFZ are used, together with GNSS observations with a sampling interval of 1 s, 30 s or 5 minutes. The difference between postseismic and averaged preseismic coordinates provides displacement time series with generally centimeter-level horizontal accuracy. The time series computed with a 5 minute temporal sampling rate captures coseismic displacement greater than nominal uncertainties at a few stations, peaking at ~30 cm on either side of the East Anatolian Fault (EAF) for the largest shock (Mw 7.8) and at ~4 m for the Mw 7.5 event, which occurred on a fault very close to station EKZ1. The time series computed every 30 s and (using interpolated satellite clock offsets) every 1 s show no evidence of significant pre/post-seismic creeping. Estimates of coseismic displacement from PPP GNSS solutions are compared with those from seismology and InSAR. Although the sensitivity of these solutions with high sampling rates can only capture significant coseismic displacement, this work serves as a preliminary exploration of a future system for automatic near-real-time imaging of surface displacement during ruptures capable of detecting complex sequences of ruptures and creeping.

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Investigating dynamic triggering in Vrancea (Romania) from the Feb 6th Turkey-Syria earthquake

DOI: 10.57757/IUGG23-4061 - LINK

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The Mw 7.8 Turkey-Syria earthquake occurred on 6th of February 2023 in central Turkey at a depth of 20 km on the active East Anatolian Fault. Approximately 9 minutes later, a ML 3.1 earthquake occurred ~1500 km away in the Vrancea Seismic Zone in Romania, at 22 km depth. Ground motion records from broadband seismic stations located near the epicentre of the Vrancea earthquake clearly show high-frequency P-wave arrivals recorded during the passage of long period, high amplitude Rayleigh waves radiated by the Turkey-Syria earthquake. We interpret this observation as first-hand evidence of dynamic triggering of crustal earthquakes in Vrancea by remote earthquakes. We estimate the probability that this particular event is a random occurrence based on the observed local seismicity rates. Furthermore, using information such as epicentral distance, hypocentral depth and source mechanism for the Vrancea earthquake, we model the transient stress tensor on the fault plane due to the passage of Rayleigh waves at discrete periods.

The Mw 7.8 Turkey-Syria earthquake occurred on 6th of February 2023 in central Turkey at a depth of 20 km on the active East Anatolian Fault. Approximately 9 minutes later, a ML 3.1 earthquake occurred ~1500 km away in the Vrancea Seismic Zone in Romania, at 22 km depth. Ground motion records from broadband seismic stations located near the epicentre of the Vrancea earthquake clearly show high-frequency P-wave arrivals recorded during the passage of long period, high amplitude Rayleigh waves radiated by the Turkey-Syria earthquake. We interpret this observation as first-hand evidence of dynamic triggering of crustal earthquakes in Vrancea by remote earthquakes. We estimate the probability that this particular event is a random occurrence based on the observed local seismicity rates. Furthermore, using information such as epicentral distance, hypocentral depth and source mechanism for the Vrancea earthquake, we model the transient stress tensor on the fault plane due to the passage of Rayleigh waves at discrete periods.

Recent Earthquakes, Seismic Hazard and Risk in the Himalayas by MCDM and Artificial Neural Network

DOI: 10.57757/IUGG23-5014 - LINK

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Earthquakes are natural disasters that are severe threat to the society and infrastructure. Recent devastating earthquakes in Türkiye has reminded us about the need for an urgent mapping the vulnerable areas, and associated risks. Recent earthquakes in Himalayas such as 2005 (M~7.6) Kashmir earthquake, Sikkim Himalaya earthquake (Sept. 2011, M~6.9), Gorkha earthquake (April 2015, M~7.8), and a more recent earthquake of 9th Nov. 2022 (M~6.6) have severely affected the whole region. We use seismological, remote sending and GIS techniques besides the multi-criteria decision models (MCDM) and artificial neural network (ANN) to estimate the earthquake risk, and coping capacity in the Himalayan region. We have integrated the Analytical Hierarchy Process (AHP), the Criteria Importance Through Intercriteria Correlation (CRITIC), and the ANN to estimate the earthquake risk. The AHP-Entropy method have been used to evaluate earthquake vulnerability and disaster coping capacity, whereas ANN have been used to estimate the earthquake probability. Our results indicate that more than 31% of the area may be under high to very high risk, whereas about 27% of the population and 31% of the infrastructure may be at high to very high risk due to seismic hazard in the region. The estimated receiver operating characteristic curve with an area under the curve ~0.83 indicates that results are reliable. The study would provide important inputs to the agencies to develop disaster mitigation strategies during any future earthquake in the region.

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S12 - Posters - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

Velocity structure and its relation to the seismicity of Datong windows region in Shanxi Province, North China

DOI: 10.57757/IUGG23-0416 - LINK

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On October 19, 1989, a surface-wave magnitude M_S 5.9 earthquake occurred in Datong-Yanggao,Two M_S 5.8 and M_S 5.6 earthquakes occurred on March 26, 1991, and November 1, 1999, respectively. Since then,aftershocks continued in this region, and this region serves as a "window" of aftershocks, it is at the junction of Datong Basin and Liulengshan Range in the northern part of Shanxi Graben, China.A high-resolution 3D P-wave velocity model of the crust was obtained with double-difference tomography using seismic data from July 2009 to June 2019. The results show that the Datong-Yanggao seismic sequence occurred, in general, within the NE rupture zone of the earthquake swarm of 1989. The sequences from 1991 and 1999 were in the rupture zone of 1989. A series of earthquakes developed in this region,which is at the intersection of multiple faults and a low-velocity anomaly of the intermediate-lower crust. A gap of length of about 3 km was found at the southwest end of the NE Dawangcun Fault. Several moderate earthquake ruptures failed to break through it. It was speculated that it may be a potential asperity. There is a possibility of an earthquake with magnitude about 5 from the gap. The relocation results for the earthquakes show that intensive small-earthquake events in Datong Window corresponding to moderate-to-strong earthquakes in Shanxi Graben were highly clustered horizontally and distributed vertically in a column.In contrast, when there was no moderate earthquake after intensive small-earthquake events, the spatial distribution of these events was scattered and dispersive.

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S12 - Posters - Recent Devastating Earthquakes Including the Feb. 6, 2023 Turkey Sequence

The effects of the devastating earthquakes in Turkey on seismicity in Romania

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The recent sequence of devastating earthquakes in Turkey (February 6, 2023) coincided with the activation of the Râmnicu Sarat seismic zone in Romania. After the first 7.8 R earthquake in Central Turkey, 2023-02-06 01:17:36.1 UTC, a 4.6 R earthquake followed shortly in Romania, 2023-02-06 01:26:20.6 UTC. This magnitude activated the NIEP (National Institute of Earth Physics) seismic warning system. On 13.02.2023, the Targu Jiu area was reactivated with a 5.2R earthquake, 2023-02-13 14:58:07.4 UTC, and three aftershocks. Shortly after, an earthquake with magnitude 4R also occurred in Croatia, 2023-02-13 15:18:49.5 UTC. Are we witnessing an overlap of events in which earthquakes with a magnitude above 7R in Turkey have reactivated other seismic zones? Before these events, we recorded an anomaly in the temperature and level of the Black Sea by the monitoring stations in Mangalia and Constanta. An analysis of the level of the Black Sea and the Mediterranean Sea before and after the devastating earthquakes in Turkey does not indicate the production of a tsunami, although an alert of this type was generated in Italy, but it shows a movement of a large volume of water that can induce seismicity. The analysis of these overlapping events in a short period of time does not indicate a direct interdependence, but an indirect one is possible. The large displacements of the faults as a result of the devastating earthquakes in Turkey can push the Black Sea microplate and affect the Vrancea seismic zone characterized by deep earthquakes with large effects.

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Black Sea microplate and affect the Vrancea seismic zone characterized by deep earthquakes with large effects.

Method for Determining the Accumulated Potential Energy of Deformation in Lithospheric Plates, Blocks of the Earth's Crust and Earthquake Prediction

DOI: 10.57757/IUGG23-3019 - LINK

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In the middle of the XX century, it was found that in earthquake-prone zones of the Earth, significant deformations (displacement of points) of the Earth's crust occur before the occurrence of earthquakes. The problem arose (Rikitake) – knowing the structure of the terrain (layering, elastic, temperature characteristics) and measuring data of the displacements of the points of the facial surface or the surface located at some depth from the facial surface (to exclude the influence of atmospheric phenomena) of the Earth, what measurement data by inclinometers and strainmeters placed there, determine the stress-strain state (SSS) of the corresponding block of the Earth and track its change over time. Thus, it is possible to trace the entire process of earthquake preparation. This process covers two stages: slow (quasi-static), fast-flowing, jump-like (dynamic: Foreshock, Earthquake, Aftershock). The first stage can last for decades.

The authors have found solutions to the corresponding quasi-static and dynamic 3D problems of elasticity theory for a layered package of isotropic plates. The accumulated potential energy of deformation is determined by the values of stresses and displacements (deformations) found. Based on regular measurements, it is possible to trace the process of accumulation of critical potential energy, leading to global destruction – an earthquake.

Based on the obtained solution, mathematically computational programs have been created to determine the potential energy of deformations and analyze SSS. According to the well-known Gutenberg-Richter formula, the magnitude of the expected earthquake is estimated. The approach can be applied in all earthquake-prone zones of the Earth.

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Time-dependency of the b-value across earthquake sequences (SUlzQUAjvbl5rAE9UCvSAY8Arp3b)

DOI: 10.57757/IUGG23-4692 - LINK

Andres Hernandez[1], Philippe Gueguen[1]
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The b-value, obtained from the Gutenberg-Richter distribution, is a critical parameter for probabilistic seismic hazard assessment. It describes the relative ratio of small to large earthquakes in a scale-free population. However, in earthquake sequences, this parameter experiences variations not accounted for in conventional seismic hazard models. Therefore, understanding the nature and impact of these variations is crucial, particularly in regions with high seismicity or prone to aftershock sequences that can last several days, weeks, or even months. Different techniques and methods are commonly employed to estimate the b-value, but they could introduce uncertainties or biases in the calculation. The amount of data used to estimate this parameter is critical in its estimation. Despite this, the behavior of the b-value during aftershock sequences and its influence on seismicity rates are not yet fully understood. In this study, we evaluate how various factors in an aftershock sequence can influence the estimation of the b-value by analyzing real and synthetic data from different contexts and characteristics. We aim to enhance the accuracy of probabilistic seismic hazard assessments and advance our knowledge of earthquake physics. The findings of this study have significant implications for improving the understanding of earthquake processes and hazard assessments. Accurate estimates of the b-value are essential for forecasting earthquake activity and assessing potential risks in seismically active regions.

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Flexible estimation approach of background stress changes based on the rate- and state-friction seismicity model

DOI: 10.57757/IUGG23-2459 - LINK

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The seismicity model based on the rate- and state-dependent friction law [Dieterich, 1994, JGR] (Dieterich model) can follow the Omori-Utsu (power-law) decay. Because the exponent (p-value) of the Omori-Utsu decay has some variety in actual aftershock sequences, the assumption of the constant background stress rate, which is often used in the Dieterich model, is inadequate. For this variety, Dieterich [1994] proposed stress increase with the logarithm of time. However, the temporal evolution of an actual aftershock sequence may have a complex feature. For such complexity, this study proposes an approach of a flexible estimation of background stress changes to fit an examined aftershock sequence.

The outline of the approach is as follows: The seismicity is decomposed into two components; a cluster and background seismicity. These two components are represented by the ETAS and Dieterich models, respectively. For the Dieterich model, the stress rates are represented with a step function; they are assumed to be constant between the occurrence time of two successive earthquakes and can vary at each occurrence time with a smoothness constraint. The stress rates, the weight of the smoothness constraint, and the parameters of the ETAS and Dieterich models are estimated simultaneously with the Markov chain Monte Carlo method in the framework of the full Bayesian approach. As a demonstration, this approach was applied to the aftershock sequence of the 1995 Kobe earthquake, and the stress rate similar to a logarithmic change with a complex feature was estimated.

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sequence of the 1995 Kobe earthquake, and the stress rate similar to a logarithmic change with a complex feature was estimated.

S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Stochastic Modelling of Earthquake Diffusion in Seismic Swarms

DOI: 10.57757/IUGG23-4442 - LINK

Georgios Michas[1], *Filippos Vallianatos*[1,2]
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Institute of Physics of Earth's Interior and Geohazards- UNESCO Chair on Solid Earth Physics and Geohazards Risk Reduction, Heraklion, Greece

Seismic swarms frequently exhibit spatial migration of event hypocenters with time attributed to external aseismic stresses, such as pore-fluid pressure diffusion, aseismic creep, or magmatic intrusion, that may act as the driving mechanism. Earthquake diffusion, observed in such cases, can be highly anisotropic, occurring preferentially along fractures and zones of weakness over wide spatial and temporal scales. The efficient modelling of the complex spatiotemporal evolution of seismic swarms, hence, represents a major challenge. Herein, we develop a stochastic model, based on the Continuous Time Random Walk (CTRW) theory, to map the spatiotemporal evolution of seismic swarms. Within this context, we describe the spatiotemporal evolution of seismicity with an appropriate master equation and the time-fractional diffusion equation (FDE). The applicability of the model is demonstrated in two seismic swarms associated with pore-fluid pressure diffusion, the 2001 Agios Ioannis (Corinth Rift) and the 2014 Long Valley Caldera (California) swarms. The analysis shows anomalous earthquake diffusion, with diffusion exponents less than unity in both cases, as well as broad waiting-times distributions with asymptotic power-law behavior. Such properties are intrinsic characteristics of a sub-diffusive process. Furthermore, the asymptotic solution of the FDE can successfully capture the main features of earthquake progression in time and space. Overall, the results demonstrate that the CTRW model can efficiently be used to map earthquake diffusion in seismic swarms.

Acknowledgements

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 00256).

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Dependence of seismic hazard on the observation time window: insights from physics-based simulated seismicity at the Eastern Betics (SE Spain).

DOI: 10.57757/IUGG23-3417 - LINK

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[1]*Complutense University of Madrid, Department of Geodynamics Stratigraphy and Paleontology, Madrid, Spain*
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In slow-moving fault systems, where the observation time window is very small compared with the long seismic cycles and the seismicity rate, the variability of the seismic hazard can be high. To assess this variability, this study develops a PSHA (Probabilistic Seismic Hazard Assessment) using synthetic seismicity. The selected site is the Eastern Betics Shear Zone (EBSZ), located at the SE of the Iberian Peninsula, the most active seismic region of Spain. The synthetic seismicity consists of a million-year catalog generated with the physics-based earthquake simulator RSQSim. This is based on a complex fault model containing slip rates, rakes, and friction properties of major faults. From the synthetic earthquake catalog, we obtained 20 sub-catalogs with random temporal distribution. The duration of each catalog was selected to replicate the historical and instrumental record used in the evaluation of the seismic hazard in the EBSZ, i.e. a thousand years. The results show a significant variability in the maximum magnitude, the slope of the Frequency Magnitude Distribution (FMD) and the annual rate of earthquakes for the different sub-catalogs. This variation has a direct effect on the seismic hazard curves calculated using the PSHA software R-CRISIS. Each return period has associated several PGA (Peak Ground Acceleration) for the different scenarios, showing the dependence of the estimated seismic hazard on the time window analysed.

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Automated machine learning for earthquake prediction from imbalance earthquake events using global geomagnetic field data

DOI: 10.57757/IUGG23-4319 - LINK

Kasyful Qaedi[1,2], Khairul Adib Yusof[1], Mardina Abdullah[1]
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[2]JX Nippon Oil & Gas Exploration Malaysia Limited, Geology & Geophysics, Kuala Lumpur, Malaysia

The advances in machine learning have led to a renewed interest in the challenging task of earthquake prediction. Analysis of the global geomagnetic field has shown promising results in earthquake precursors study. However, applying this approach to develop an accurate earthquake prediction model has proven to be difficult partly because of the sophistication of the data. This study presents an Automatic Machine Learning (AutoML) technique for handling complex geomagnetic data and imbalance earthquake events by selecting the optimum machine learning model through Bayesian optimization. Global geomagnetic data and earthquake events that occurred between 1970 to 2020 was used in this study. Sampling techniques approaches showed promising results to solve the problem of an imbalance dataset, essential features were extracted and a multi-class classification model was developed using sample dataset that consists of oversampling and undersampling data. Sample and Raw models were developed from two different dataset, the result shows that the Sample model selects Neural Network as the best model, outperforms Raw model. Raw model shows 94% accuracy, 44% Matthew Correlation Coefficient (MCC) and 0% F-1 score, meanwhile Sample model shows 89% accuracy, 86% MCC and 89% F1-score. It is found that a neural network multi-class classification model addresses the solution to earthquake prediction challenges when using global geomagnetic data.

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Forecast of maximum amplitude immediately after a large earthquake through the extreme value analysis of continuous seismogram

DOI: 10.57757/IUGG23-0542 - LINK

Kaoru Sawazaki[1]
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As aftershock activity follows the Omori-Utsu law and is at the highest in the early lapse times, detection capability of earthquakes becomes poor at this stage. At the same time, however, it is strongly desired to provide reliable aftershock forecast as early as possible. To overcome this issue, we have proposed to use interval maximum amplitude (IMA) of a continuous seismogram, instead of the deteriorated earthquake catalog, and apply the extreme value statistics. Theoretically, the IMAs follow the non-stationary Frechet distribution, which is one of the three extreme value distributions. By applying the maximum likelihood method to the IMAs, we can estimate parameters that control the NFD. Using the Markov Chain Monte Carlo (MCMC) method, we can randomly select the NFD parameter sets from the posterior distribution. These parameter sets can be used to compute the number and probability that the IMA exceeds arbitrary values within assigned time periods. We applied this method to seismograms of four aftershock sequences occurred in Japan. Among them, only one case (Mw6.2 largest foreshock of the 2016 Kumamoto earthquake) was followed by the larger event (Mw7.0 mainshock of the Kumamoto earthquake) 28 hours later. Statistical analysis of one hour IMAs showed very high probabilities of further large amplitude after the Kumamoto foreshock, while relatively small probabilities for other three aftershock sequences.

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Visualization of aftershock forecasts driven by user needs

DOI: 10.57757/IUGG23-4881 - LINK

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The U.S. Geological Survey releases aftershock forecasts following large (M5+) earthquakes in the U.S. and associated territories. Forecasts show the expected number (and range) of aftershocks in a specified area for various magnitude thresholds and time durations. Forecasts are released using a product template that contains tables and text. Visualizing these aftershock forecasts can more effectively communicate this information. In particular, we seek to identify which forecast visualizations (including maps) can serve a variety of user groups. First, we hold workshops with members of target user groups, including emergency managers, civil engineers, critical infrastructure operators, science communicators, and the media. In these workshops, users perform activities to elicit specific user needs on the dimensions of aftershock forecast information needed by their role (informational needs) and how this information would optimally be displayed (product needs). We then develop a suite of forecast graphics and maps based on these informational and product needs. We furthermore plan to run a user experiment to test a subset of these forecast products. In the experiment, participants from these target groups will use different forecast products to perform decision-making tasks based on common use cases of aftershock forecasts. Such an experiment can reveal the characteristics of forecast products that can effectively communicate the forecast across user groups. Workshops and experiments will be held with participants from the U.S., Mexico, and El Salvador to identify cross-cultural components of effective forecast communication. We present preliminary results from several user workshops and discuss next steps in the research agenda.

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S13 - Posters - Development, Testing and Application of Earthquake Forecasting Models

Characteristics of b-value and envelope of MS ≥ 6 earthquake sequence with foreshocks in Chinese mainland

DOI: 10.57757/IUGG23-1320 - LINK

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Large earthquakes are usually followed by decaying aftershocks. In some cases, a large earthquake is followed by even larger earthquakes. To estimate seismic hazards of earthquake sequence, it's necessary to make sure whether the mainshock has already happened. There is no effective method yet to distinguish foreshocks from aftershocks. However, statistical analysis may tell us some useful clues. Since 2010, 35 $M_S \geq 6.0$ earthquakes have occurred in Chinese mainland, of which 6 $M_S \geq 6.0$ earthquakes have foreshocks with magnitude larger than 5. Based on foreshock traffic light system (Gulia and Wiemer, 2019), *b*-positive (van der Elst, 2021) and envelope method (Lippiello *et al.*, 2021), we explored the temporal characteristics of *b*-value in the Gutenberg–Richter law and the envelope of foreshocks with $M_S \geq 5.0$ by using catalog and waveform of 6 $M_S \geq 6.0$ earthquake sequences and tried to propose a real-time foreshock classification method. The preliminary studies show that the temporal variation and the envelope may be useful to recognize foreshocks. For example, the evolution of foreshock sequence of 2019 Yangbi M_S 6.4 earthquake can be divided into 3 periods. In the first and second period, the foreshock sequence varied like common aftershock sequence, but the seismicity rate unusually accelerated preceding the mainshock. And the study of waveform of $M_S \geq 5.0$ foreshocks before Yangbi M_S 6.4 earthquake shows that the envelope presents an atypical sawtooth profile and the corresponding β-value is smaller than 0.4 which is much lower than the normal value.

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S14 - Posters - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Multiparameter statistical study of the crustal seismic secquence started on February 13th, 2023 in Targu Jiu area (Romania)

DOI: 10.57757/IUGG23-3355 - LINK

Cristian Ghita[1], Bogdan Enescu[2], Eugen Oros[3], Andreea Craiu[3], Marius Craiu[3], Iren Adelina Moldovan[3], Lucian Palangeanu[3], Anica Placinta[3]
[1]National Institute for Earth Physics, Seismology and Lithosphere Structure, Magurele, Romania
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The purpose of this study consists in the analyses of statistical parameters of seismicity, the released energy and the Coulomb stress change (deltaCFS) for the ongoing sequence started with a foreshock (Mw4.8) on 13.02.2023, followed by the main shock on 14.02.2023 (Mw5.4) in Romania, Targu Jiu area. The maximum macroseismic intensity reported in the area was VII MSK and PGA 0.15g. The seismic sequence (700+ events in less than one week) occurred at the contact between the Getic Depression, to the south, and the Southern Carpathians, to the north. The epicentral area is tectonically complex with various types of faults. The sequence may have activated normal faults, oriented WSW - ENE, as indicated by the focal mechanisms. Another sequence was recorded in the study area in 2012 (Radulian et al., 2014), with smaller earthquakes (maximum magnitude of 4.5), which occurred on reverse faults located south-east from the current sequence. The aftershocks will continue in the following months, but their number will decrease over time, according to the Omori law, which fits the preliminary data well. The seismic energy release will be computed using Mw resulted from the seismic moment (Mo). Aftershocks distribution and macroseismic maps will be used to improve fault characterization, which will facilitate the estimation of deltaCFS. We may tackle as well the debated question of a possible connection between the major earthquakes in Turkey on February 5 and 6 and the crustal earthquakes in Romania.

This paper was financed by Nucleu PN23360201 SOL4RISC, and AFROS PN-III-P4-ID-PCE-2020-1361.

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S14 - Posters - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Seismicity patterns from global to regional and local scale - geotectonic reality or just pure mathematical modeling

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The seismic activity of Romania, is part of the Mediterranean-Asian seismic belt. It follows the chain of young mountains starting from Southern Europe, continuing through Turkey, Iran, the Caucasus and Central Asia. In this framework, the identification of series of strong earthquakes allows, through the application of advanced techniques of artificial intelligence and data science, to extract certain patterns of global, regional and local seismicity. Our paper has as final goal the forecast of crustal and subcrustal strong events in Romania, considering the application of advanced AI and Data Science techniques to extract hidden patterns from data sets, and to provide analytical arguments for the correlation of seismicity. We review seismic patterns involving adjacent tectonic plates, the migration of earthquakes along plate boundaries, but also intraplate seismic models involving Romanian crustal and subcrustal earthquakes. In the continent-continent collision between Eurasia, Africa and India we remarked not only eastward but also a westward migration such as the one in the years 2020-2022 originated in Indonesia and Myanmar then moving from Hindukush, Iran, East Turkey, Syria, West Turkey, and ended with a moderate intermediate depth earthquake in Vrancea. A much higher velocity migration of two month only started in the Indian Ocean, Indonesia, Iran and culminated in Turkey-Syria with the Mw 7.8 event of February 6, 2023. The highly debated connection of the crustal seismic activity from Vrancea and Targu Jiu, Romania, starting immediately after the 7.5 earthquake from Turkey (5.02.2023) will be discussed. Work funded by SOL4RISC Nucleu and AFROS Projects

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S14 - Posters - New Advances in Understanding The Earth'a Crust Dynamics in the Light of Solving the Problem of Earthquake Forecasting

Self-similarity of active fault systems and distribution of earthquake epicenters

DOI: 10.57757/IUGG23-0383 - LINK

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We analyse the fractal dimension of active fault systems versus the fractal dimension of earthquake epicentres in the Greater Caucasus, Altai-Sayan, Baikal, and Kamchatka Regions. In particular, for each of the four regional systems of active faults the box counting and correlation dimensions, D_0 and D_2, were computed based on the Active Faults of Eurasia Database (Bachmanov et al., 2017). The data permit distinguishing fractal dimensionality of the vertical, lateral and extensional displacement faults. The obtained regional values of D_0 and D_2 are compared to the regional distributions of the C-coefficient of the Unified Scaling Law for Earthquakes (USLE) that compliments to the a- and b-values of the classical Gutenberg-Richter relationship with C, an estimate of fractal dimension of earthquake epicentres at a given site. We used maps of the USLE coefficients in the selected four regions from (Kossobokov&Nekrasova 2018a, 2018b; Nekrasova&Kossobokov 2020, 2022).

The comparison of fractal dimensions of active faults and earthquake epicentres has shown up higher values of dimensionality of regional fault systems, which evidence, presumably, a large number of locked, dormant, silent, or seismically inactive faults. From the viewpoint of instrumental/operational seismology, the tectonically active systems of blocks-and-faults reflect fragmentation of the lithosphere with a significant redundancy.

In addition, for each of the four regions a cross-comparison of D_0 and D_2 versus C at the site of the observed largest earthquake is performed.

The study is carried on in the framework of the Russian State Task of Scientific Research Works of IEPT RAS (0143-2019-0006).

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Modelling out-of-plane signals in the global Earth: first results from a flat subducted slab

DOI: 10.57757/IUGG23-4917 - LINK

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Traditional seismology often assumes that seismic waves travel through the mantle within the great circle path, in the sagittal plane along sources and receivers. Since the 1990s it was already known that subducted oceanic lithosphere in the mantle could laterally deviate the path of seismic signals, which arrive with different angles (out-of-plane) at an array of sensors at teleseismic distances. Detecting these signals with array processing techniques, and the consequent back-projection, have provided valuable information on the location of both ancient and actual subducted slabs. This hypothesis was also tested with synthetic seismograms by a study which carried out a preliminary modelling of P-to-P out-of-plane signals, providing hints on "how and where to look".

In this work, we conduct 3D waveform modelling to assess to which extent these out-of-plane signals can be used to infer physical properties of the slabs (e.g., thickness, age, orientation, velocity, and density contrasts). An important aspect to investigate is how these slabs affect the waveforms of both P and S out-of-plane signals, and if these signals are influenced by the presence of oceanic crust. Conversions P-to-S and S-to-P could provide additional constraints. Although still at the initial stage, the experiment shown here provides already useful information for more complex and realistic setting which will be tested in the future.

Furthermore, LLSVPs will be tested as cause for deep mantle out-of-plane signals generated from their boundaries.

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S15 - Posters - Boundary Layers in Earth's Mantle: Origin, Structure, and Influence on Convection

Mapping strong topography of mantle reflectors beneath southern Asia

DOI: 10.57757/IUGG23-4918 - LINK

Federica Rochira[1], *Christine Thomas*[1]
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Precursor signals are a powerful tool for mapping topography of mantle discontinuities, which are sensitive to the thermal and compositional structure of the mantle. The depth of mantle discontinuities is usually estimated by using the measured differential traveltime between the main arrival and its precursor. However, this method ignores potential travel path deviations which influence the traveltime of precursor signals. Here, we use a different approach that considers directivity information as well as traveltime measurements to infer depth and location of mantle reflectors. We analyze events occurred in Indonesia and recorded at the broadband stations in Germany and in Morocco. Applying seismic array techniques, we measure slowness, backazimuth and traveltime of the signals and use this information to back-project to the point of reflection. We observe SS and PP reflections located beneath southern Asia and in the depth range between 100 and 1600 km in the Earth's mantle. SS reflections show a clear trend from shallower depths (< 500 km) in the south-eastern part of the studied area to lower depths (> 500 km) in the north-western part. The location of most of deeper reflectors seems to correlate with a high velocity anomaly located beneath south Asia. Instead, shallower reflectors correlate with a prominent low velocity anomaly beneath south-east Asia. We compare the observed data with synthetic seismograms using 3D waveform modelling and test which structures in the Earth's mantle (i.e., plume and slab) can potentially generate the strong topography observed in the data.

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S15 - Posters - Boundary Layers in Earth’s Mantle: Origin, Structure, and Influence on Convection

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 the reflection coefficient for P and SH underside reflections using velocity perturbations resulting from aligned minerals above and below the 410 km discontinuity for different deformation scenarios. Our results indicate some differences in amplitude and polarity patterns of reflection coefficients of 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. The amplitudes of P and SH waves are influenced by the effect of angle of incidence and polarity reversal of the P and S waves are observed for some deformation styles. Furthermore, water content of wadsleyite plays an important role in creating the polarity reversal of the waves compared to the case of dry wadsleyite.

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S16 - Posters - Earthquake Source Mechanics

Source parameters of recent moderate-size subcrustal earthquakes of Vrancea region (Romania)

DOI: 10.57757/IUGG23-0431 - LINK

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[1]*National Institute for Earth Physics, Seismological Laboratory, Bucharest - Magurele, Romania*
[2]*National Institute for Earth Physics, Seismic Network, Bucharest - Magurele, Romania*

The seismic source parameters (seismic moment, corner frequency, source radius, static stress drop) of the moderate-size earthquakes which occurred in the Vrancea intermediate-depth seismogenic region (Romania) during the last decade are determined using the spectral analysis of S waves. The events have moment magnitudes between 4.5 and 5.7, and depths in the range from 90 to 150 km.

The observed data are high-quality horizontal acceleration records. The source parameters are estimated from the displacement amplitude spectrum of the transverse component of motion. The duration of the time windows selected to compute the Fourier spectra is dependent on the earthquake magnitude and amplitude behaviour of the wave trains.

The relations between the retrieved source parameters have also been examined. The trend of increasing fault radius with increasing seismic moment is visible, however the slope of the regression line is clearly smaller than the theoretical value predicted by the theory of self-similarity. The tendency of decreasing stress drop with decreasing seismic moment can also be noticed, which might indicate a deviation from the constant stress drop model.

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S16 - Posters - Earthquake Source Mechanics

The source parameters estimation of the intense seismic sequence recorded in 2023 - Tg. Jiu area, Romania

DOI: 10.57757/IUGG23-4457 - [LINK]

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[1]National Institute for Earth Physics, Romanian Seismic Network, Magurele, Romania
[2]National Institute for Earth Physics, National Data Center, Magurele, Romania
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An intense seismic activity started in February 2023, close to Targu Jiu city, in the Oltenia region (Romania). The strongest events, characterized as doublet earthquakes, occurred on 13th and 14th February, the first shock with ML=5.2, and respectively the second shock with ML=5.7. These main shocks were followed by specific seismicity bursts (in the first week, about 800 foreshocks were registered). The focal depth of the events ranges from 1 to 20 km, most of them being situated in the 10-20 km depth interval. The area of interest is tectonically complex with various types of faults and it takes place at the contact between the Getic Depression, to the south, and the Southern Carpathians, to the north. The seismic sequence of Tg. Jiu occurred in the northern part of the Valea Motrului-Valea Oltetului area (part of Getic Depression) and is characterized by extensional faults, which show a general direction of ENE - WSW. The aims of this study are the estimation of the source parameters (MW, M0, f0), along with the focal mechanisms for events with ML≥3. For the seismic source delineated in Tg. Jiu area, the stress field has an extensional stress regime (σ1 almost vertical), with maximum horizontal stress (SHmax) oriented in the NW-SE direction. The resulting SHmax orientation and normal fault regime with a radial component (R′=0.5) are consistent with the observed geological setting. The results of this study are useful for assessing past and current tectonic activities and future research of the epicentral area.

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geological setting. The results of this study are useful for assessing past and current tectonic activities and future research of the epicentral area.

Source parameters for seismicity in Mexico City since 2010 to 2020

DOI: 10.57757/IUGG23-4451 - LINK

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In the historical catalog published by the SSN, discrepancies have been detected in the depths and magnitudes of ancient earthquakes with epicenters in Mexico City and the State of Mexico; in most cases, due to wrong velocity models used to calculate the hypocenter of these earthquakes (mainly those recorded before 2010). Recently, structure models have been estimated for some areas of Mexico City, which has allowed for a more reliable depth calculation. Regarding the magnitudes, several earthquakes were reported with a few readings, allowing for a misdetermination of magnitude value. In this research, we made a careful relocation of these events, and the magnitude previously calculated was also corroborated with the determination of the seismic moment magnitude; additionally, for the events meeting requirements such as being of magnitudes greater than 2.5 and recorded in more than five stations, we obtained focal mechanisms through several techniques such as Focmec, Fpfit, and Hash, all of them inside the Seisan package. In addition, the inversion was performed using the ISOLA method, which occurred between 2010-2021.

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Repeating earthquakes in Northern Chile, from true repeaters to deep repeaters

DOI: 10.57757/IUGG23-3201 - LINK

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At the northern Chilean subduction zone, the IPOC network has been monitoring seismicity since 2006. For the observation time until 2021 a recent catalog has been published holding more than 182,000 events. We have performed a complete template matching run on the continuous seismic data using this catalog, enabling us to identify a large amount of repeating earthquake families. Many identified family members were not in the original catalog, but solely identified by the template matching. High data quality and long observation time allow analyzing these sequences in detail.

Using a relative relocation approach based on wave phase based cross correlation refined s-p travel time differences, we are able to compute highly precise relative locations for these events. Paired with very recently obtained stress drop information, we are able to distinguish between true repeaters and similar events. This distinction is important, especially when the families are utilized as creep proxies and are being compared to the plate convergence rate or plate coupling.

The repeaters in the vicinity of the Mw8.1 2014 Iquique earthquake show different characteristic behavior reflecting signatures corresponding to pre-, inter-, and post-seismic phase of a megathrust event. We observe clear precursor patterns, burst reactions and unresponsive families simultaneously. Their cumulative slip and characteristic decay rates correspond well with the slip and after slip patterns reported for the Iquique event.

Interestingly, repeating series are also found in deeper parts of the subduction channel, where the classical repeating earthquake theory loses validity.

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S16 - Posters - Earthquake Source Mechanics

Physics-Informed Neural Networks for modeling slow slip events in a spring-slider system with a rate and state friction law

DOI: 10.57757/IUGG23-0328 - LINK

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In the Physics-Informed Neural Networks (PINNs) approach, we construct neural networks that can solve the physics-based equations by minimizing the loss function which involves the differential equations and initial / boundary conditions [Raissi et al., 2019]. This approach has been recently adopted in many research fields because it not only provides the mesh-free framework for forward problems but also easily obtains solutions for inverse problems. In seismology, a spring-slider model is often used to simulate fault slip evolution [Yoshida and Kato, 2003]. In this study, we applied PINNs to this simulation in the spring-slider model that combines quasi-dynamic equations of motion [Rice, 1993] and rate and state friction law [Ruina, 1983]. By assigning appropriate frictional parameters, we successfully reproduced slow slip events (SSEs). Unlike the time-adaptive Runge-Kutta approach that is usually used in solving these equations, PINNs can solve the equation with equidistant collocation points. This indicates the high interpolation ability of PINNs. To incorporate the temporal causal structure, we also applied the Causal-PINNs [Wang et al., 2022] to the same problem. We found that the Causal-PINNs obtained a similar simulation result with faster calculation speed and higher accuracy compared to original PINNs. In addition, we estimated the frictional parameters by adding the misfit term between the observed and calculated slip velocity data to the loss function. As a result, all frictional parameters are optimized from the synthetic data with added noises. These results imply that the PINNs approach is effective in earthquake cycle simulation and frictional parameter estimation.

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The ruptures were stopped by the local tectonic structures – cases from two Mw6.6 strike-slip earthquakes in China in 2022

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A series of strike-slip faults developed in China, such as the Xianshuihe Fault, Honghe Fault, etc. Moderate intraplate strike-slip earthquakes are more active and hazardous in China. A series of moderate intraplate strike-slip earthquakes occurred around Tibet Plateau in 2022, including the Menyuan Mw6.6 earthquake, the Luding Mw6.6 earthquake, and the Maerkang Mw5.8 earthquake.

An Mw6.6 earthquake struck Menyuan, northeast of Tibet Plateau in China, on 7th January 2022. The earthquake destroyed the high-speed railway near the epicenter. An Mw6.6 earthquake struck Luding, southeast of Tibet Plateau in China, on 5th September 2022, which caused severe damage.

The bend, step-over, and other local tectonic structures play a key role in the beginning and ending of strike-slip earthquakes. The geodetic and regional seismic data make it possible to investigate the rupture process of earthquakes of moderate magnitude. The updated China Earthquake Network included over two thousand broadband stations, three thousand strong motion stations, and ten thousand MEMS sensors.

The rupture processes of the two earthquakes are investigated based on regional, teleseismic, and geodetic data. Combined with the relocated aftershocks distribution by other researchers, the results show that the rupture started at the bend of the strike-slip fault and was stopped by the local tectonic structures. It implies that it would be possible for us to estimate the earthquake potential rupture zone based on the tectonic structures in the strike-slip fault zone.

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Source mechanisms of the earthquake swarms linked to the 2021 Fagradalsfjall volcanic eruption (SW Iceland)

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We retrieved source mechanisms in the moment-tensor description (MT) of an intense earthquake-swarm activity on the Reykjanes Peninsula (SW Iceland) in 2020 to 2021 preceding the Fagradalsfjall volcanic eruption in March 2021. We inverted displacement amplitudes of the direct P- and S-waves from a local network REYKJANET complemented the network of the *University of Cambridge* and by the near stations of the regional SIL network; a total of about 30 stations covering well the Fagradalsfjall are used. For a sufficient resolution of the source mechanism an accurate enough response of the medium the Green's function (GF) is demanded. For this purpose we used a 1-D velocity model for the Reykjanes Peninsula by Vogfjörd et al. (2002). For the GF construction, we applied the ray theory. Substantial effort has been devoted to facilitate a batch processing of the events, first of all it means to allow the ANRAY to work in a semi-automatic regime, which is not its inherent mode of work. As a result, we have a comprehensive tool for retrieval of MTs on the Reykjanes Peninsula. We demonstrate its usefulness by treating a set of several tens of events. Source mechanisms of some of them are compared to those obtained by ISOLA, a software for processing of regional earthquakes, which however applies different data and different approach. Our set of MTs retrieved provides a deeper insight into the mechanism of faulting due to dyke propagation in the region in question from the beginning of 2020 to March of 2021.

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Time sequence of the seismicity and relationship with the mid-crustal reflector in Iwaki area, northeastern Japan

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The 2011 Tohoku-Oki earthquake with M 9 occurred on March, 11, 2011. Many remarkable changes of crustal activity were observed in Japan after the earthquake. The Iwaki area, northeastern Japan, is one of the places that the seismic activity increased drastically. The high seismic activity area is located in a triangle area with one side length of about 50 km. The two boundaries at the depth of around 30 km and 15-23 km were detected in this area by the analysis of waveforms (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. The relationship between the time sequence of the seismicity (data of Japan Meteorological Agency) and the reflector of the mid-crustal boundary (Usuda et al., 2022) is researched in this study. The mid-crustal boundary dips northeast direction. The seismic activity began at just above the mid-crustal reflector at the southern part of the reflector. The seismicity spread to wide area on and around the mid-crustal reflector. The seismicity gap was found at the central part of the area. The large intraplate earthquake, 2011 Hamadoori earthquake (Mw 6.6), occurred on April 11, 2011 at the seismicity gap. The active seismicity area formed large triangle area. In Japan, it has been suggested that the source of large earthquake is related to crustal fluid. It is considered that the crustal earthquakes in Iwaki area are also related to the crustal fluid.

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Megathrust complexity delimited the up-dip extent of slip during the 2021 Chignik, Alaska Peninsula earthquake

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The up-dip extent of slip during large megathrust earthquakes is important for both tsunami excitation and subsequent tsunami earthquake potential, but it is unclear whether frictional properties and/or fault structure determine the up-dip limit. A finite-fault slip model for the 2021 M_W 8.2 Chignik, Alaska Peninsula earthquake obtained by joint inversion and modeling of geodetic, seismic, and tsunami observations provides unusually good constraints on the up-dip edge of the slip. Rupture initiated ~35 km deep and propagated unilaterally northeastward with large-slip (up to 8.4 m) distributed over a depth range of 26 to 42 km beneath the continental shelf. Aftershocks concentrate up-dip of the coseismic slip around a strong megathrust reflector with high Coulomb stress change. The ~25 km deep up-dip edge of slip strongly correlates with a change in plate interface reflectivity apparent in reflection profiles, indicating that a structural and frictional transition provided a barrier to shallower rupture.

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Revised Empirical Relationships for Estimation of Earthquake Magnitude: Application of Machine Learning

DOI: 10.57757/IUGG23-4891 - LINK

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Centre for Ocean- River- Atmosphere and Land Sciences CORAL, Kharagpur, India

In this study, we developed a new empirical relation between various source and rupture parameters such as moment magnitude (M), surface rupture length (SRL), subsurface rupture length (RLD), rupture width (RW), rupture area (RA), and average (AD) and maximum slip (MD), based on an extensive updated database. A log-linear regression was used to study 402 earthquakes that occurred between 1857 and 2018, ranging in magnitude M~4.5-9.2, with various faulting mechanisms. All fault mechanisms correlate well with M-SRL, M-RLD, M-RW, and M-RA. In contrast, the M-AD and M-MD correlate moderately for reverse faulting, whereas the correlation is relatively better for other fault types. The results were compared with previous studies and found to be revised. On the other hand, the log-linear equations predict a single magnitude value as a function of a single fault parameter independent of the values of other fault parameters, which may lead to inconsistency. This limitation has been addressed by applying machine learning techniques to estimate the earthquake magnitude while simultaneously using all fault parameters to ensure consistency. We also investigated the performance and applicability of an artificial neural network (ANN) and a gradient-boosting machine (GBM) regression technique. Our analysis shows that GBM outperforms regression equations in estimating earthquake magnitude, but ANN outperforms both. The result of this study would be extremely useful for paleoseismic studies where reliable estimates of earthquake magnitudes and other source parameters are often unavailable from published literature.

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Modelling dynamic rupture in olivine-based subducting slabs: From a microscopic to a mesoscopic perspective

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[2]Universidad de Extremadura, Departamento de Física- Centro Universitario de Mérida, Mérida- Badajoz, Spain

A common mineral for subducting material is olivine, which is a magnesium-ferrosilicate with varying amounts of iron and magnesium. The purpose of this work is to investigate the rigid rupture process of crystalline olivine from an atomistic perspective and to estimate the energy released during the breakdown process of the material. In this study, ab initio calculations have been performed based on the well-known Density Functional Theory (DFT). As a first step, we calculated the electro-structural energy minimum of the unit cell of olivine at 24 GPa, which corresponds to the pressure condition of the subducting slab at a depth of 700 km. To obtain reference stress-strain curves, the relaxed unit cell was strained under a variety of shear distortions. In this way, we were able to calculate the theoretical total energy released by the subducting material during atomistic rupture. To broaden the atomistic energy budget to a macroscale rupture mechanism (i.e., with the size of the fault), we developed a modular multiscale fracture model. Several grain ruptures are simulated in this manner, with each grain containing different crystallographic directions within a polycrystalline olivine matrix. A stochastic simulation scheme was applied to this model to compute multiple grain ruptures and thereby estimate the energy involved in a macroscale rupture. The results obtained were compared to the average moment-scaled functions that were obtained for very deep earthquakes in the Peruvian-Brazilian subduction zone.

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Source characteristics of earthquake swarms in southwest Australia

DOI: 10.57757/IUGG23-1332 - [LINK]

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Southwest Australia is the most seismically active area in the stable continental region of Australia. The Southwest Australia Seismic Network (SWAN) is a temporary broadband network of 27 stations that has been deployed since October 2020. The SWAN network detected a major earthquake swarm, termed the Arthur River swam, that comprised of 3000+ events total have been located as of December 2022. The swarm appears to be ongoing. Several clusters of other small earthquake swarms are observed within the SWAN array. It is usually assumed that the source of an earthquake swarm is within a brittle fault damage zone, which likely to be very permeable. However, it is not clear that every swarm earthquake is related to fluid motion in a fault damage zone.

We estimate Centroid Moment Tensors of the earthquakes with magnitudes ranging from 4.2 to 5.2 MLv (3.9-4.8 MLa) that occurred during earthquake swarms in order to assess the detailed structure of the focal zone. The centroid moment-tensor is obtained from full waveform modelling through a 4D spatiotemporal grid search allowing for time shifts around the origin time. The inversion generates a set of solutions that constrain the depth, centroid's location and the moment tensor. Our initial analysis for the largest earthquake (MLv 5.2) shows a reverse faulting mechanism at depth of 1 km. We have tested a range of frequency bands and concluded that our local Earth model, developed using earthquakes recorded by SWAN, sufficiently simulates seismic waves up to 0.15 Hz.

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Long-term activity change in Very low-frequency earthquakes in the south Ryukyu Trench

DOI: 10.57757/IUGG23-4841 - LINK

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Very low-frequency earthquakes (VLFEs) occurred regularly along the south Ryukyu Trench. The activity was concentrated at the slab depth of 10-20 km along the trench axis. The VLFEs occurred every two to three months for a few days in a seismic swarm. Long-term variations in VLFE activity reflect temporal changes in the degree of strain accumulation and release in the plate interface. Therefore, I investigated the long-term changes in VLFE activity in the south Ryukyu Trench. First, I analyzed continuous waveforms by NIED F-net and Taiwan BATS broadband seismic stations from 2003 to 2019. Second, I detected the VLFEs using the cross-correlation technique by Asano et al. (2014). As a result, I detected VLFE candidates with similar waveforms to those known as regular earthquakes as template events.

The VLFE activity in south Ryukyu Trench decreased gradually from 2003 to 2009. The degree of VLFEs decrease was greater west of the center of the clusters and more minor to the northeast. In 2002, a series of MJ 7.0 earthquakes (March 26, 2002) and MJ 6.9 (March 31, 2002) interplate earthquakes occurred in the west and south of the VLFE clusters. The afterslip associated with the March 26, 2002 earthquake occurred in the north of western part of the VLFE clusters (Nakamura, 2009). These would have caused stress changes in the plate interface in the central and western parts of the VLFE clusters and would have activated the VLFEs. After then, the VLFE activity would have decreased gradually, accompanying the stress release.

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Improving pseudo-dynamic earthquake source modeling with the non-stationarity of source parameters

DOI: 10.57757/IUGG23-1529 - LINK

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Pseudo-dynamic source modeling is an efficient tool to simulate near-source ground motions and investigate their characteristics. It combines the advantages of both kinematic and dynamic source modeling. In other words, it keeps the computational efficiency of the kinematic source modeling, while the input values of the pseudo-dynamic source models are constrained by analyzing a set of dynamic source models. In this study, we investigated the non-stationary characteristics of the dynamic source models. Although the pre-existing pseudo-dynamic source modeling method assumes the stationarity of source parameters, it is reasonable to expect the non-stationary distributions of kinematic source parameters such as asperities. We carefully analyzed a set of dynamic source parameters, focusing on their non-stationary distributions. Then the non-stationary components (trend part) were extracted by using elliptical Gaussian surfaces. After extracting the trend part, we confirmed that the source statistics of the remaining distribution (fluctuation part) show a reasonable level of stationarity. We further plan to simulate near-source ground motions by using the separated source models into trend and fluctuation parts. Then we investigate the contribution of each source component to the frequency contents of near-source ground motions. We expect to improve the pseudo-dynamic source model significantly by considering the non-stationarity of source parameters and dealing with the trend and fluctuation parts separately.

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Shedding light on the rupture mechanism of small earthquakes in the Alps and Dinarides: Stacked-waveform MT Inversion

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Full waveform-based moment tensor (MT) inversion allows for studying complex rupturing processes, including volumetric changes. However, small-magnitude earthquakes in swarms or aftershock sequences often have a poor signal-to-noise ratio that hinders full waveform-based MT inversion. We overcome this limitation by exploiting waveform similarity of events that occur close in space and rupture the same fault, as commonly observed for swarms and seismic sequences. By stacking the waveforms of such events, characteristic features are amplified while noise is suppressed. Consequently, full waveform-based MT inversions can be applied to obtain a composite mechanism. In our work, we apply the waveform-based network-similarity clustering toolbox Clusty to identify multiplets within seismic sequences in the SE Alps and N Dinarides between 2016 and 2019. We stack their waveforms and subsequently perform probabilistic MT inversions. The resulting composite mechanisms are interpreted along with MTs of single, larger events and known local faults. We discuss the limits of the method and investigate the required thresholds for waveform similarity and stacking approaches. We provide a comprehensive workflow that links two toolboxes: Clusty for event clustering and Grond for MT inversion. In future works, we aim to extend our approach to remote earthquakes, which are often monitored only by a few distant stations with poor SNR.

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Stress distribution evaluated for the western India-Eurasia collision zone from a declustered catalogue of earthquake focal mechanism solutions

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A declustered catalogue of 324 focal mechanism solutions has been used to evaluate the stress distribution of the western part of the India-Eurasia collision zone, and its kinematics and seismotectonic implications. In this study, we have obtained stress fields for different tectonic settings identified based on geology, tectonics and focal mechanism availability. The results show NE-SW trending principal stress axis (σ_1) with compression for the Himalayan seismic belt, while the Karakoram-Tibet region exhibits a strike-slip stress regime. Within the Himalaya region, the western region i.e., between 75° and 77° E latitudes shows arc-oblique compression (NE-SW) in contrast to the arc-normal compression (NNE-SSW) in the central Himalaya (beyond 77°); consistent with available GPS vectors. The stress field for the aftershock sequence of the 2005 Kashmir earthquake and its epicentral region (Hazara Syntaxis) is distinct from its adjacent regions (Pamir, Nanga Parbat and Hindukush), but comparable with that of the Central Himalaya, suggesting a Himalayan-type stress field. The Karakoram fault and Kaurik Chango Rift exhibit transpressional (σ_1: NNE-SSW) and transtensional (σ_1: N-S σ_1) motion, respectively. Further, the varying stress ratio (0.07-0.9) suggests the role of the intermediate stress axis (σ_2) in the areas of low-stress ratios and the stress field heterogeneity, hence varying seismic hazard.

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Characteristics of Donachiwada fault at Koyna, India from focal mechanism studies

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Recent seismicity patterns and seismological investigations affirmed that the Donachiwada fault is the main causative fault for earthquakes in the Koyna region. However, the characteristics of this fault zone at depth is not yet well known. In this study we have selected a potential block of this fault zone and estimated the focal mechanism solutions of earthquakes of M_L~2 of this block recorded during 2015 – 2019 on a combined seismic network i.e. short-period borehole and surface broad-band seismic stations. Out of 29 earthquakes from a 4 x 4 km^2 block of the Donachiwada fault, we selected 10 events which resulted in well constrained solutions. Fault plane solutions are dominated by strike-slip faulting, consistent with a stress controlled by a horizontal compression (P-axis) with an EW trending T-axis. One of the fault planes of each best fit mechanisms are well correlating with the trend of the Donachiwada fault which is aligned in NNE-SSW. Most of the events suggest a steep west dipping nature of the Donachiwada fault. An event that occurred on 19 May 2017 earthquake of M_L 2.6 of this block provides the first seismic evidence of thrust faulting in this region. Also, a 3-D local earthquake tomographic inversion on high-quality travel time data shown an increase in P-wave velocity and a high V_P/V_S anomaly beneath this fault trace. The anomalies obtained by the tomography study are well correlating with the steep dipping planes of the fault zone.

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S16 - Posters - Earthquake Source Mechanics

Focal Mechanisms and Seismicity of local earthquakes beneath the Sikkim Himalaya

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The Himalayas which formed as a result of collision between the Indian and Eurasian plates has been a hotspot for great earthquakes. With an aim to understand the origin of seismicity in and around the northeastern state of Sikkim in India, 27 broadband seismic stations were deployed across the Sikkim Himalayas and Himalayan foreland basin (northern part of West Bengal). The continuous operation of the network since April 2019 to present day has enabled the acquisition of quality data with excellent azimuthal coverage. We have used local earthquakes (epicenter < 200km) detected by the network to study the seismotectonic activity of the region. Progressive relocation of these earthquakes using multiple algorithms facilitated in locating the hypocenters with great precision. We then employed full-waveform moment tensor inversion to obtain the fault plane solutions. Earthquakes concentrated in the central part of the study region are located in the upper crust along the dipping surface of the Main Himalayan Thrust. Whereas, earthquakes concentrated diagonally along the Dhubri-Chungthang Fault Zone are located at mid to lower crustal depths. These crustal earthquakes are observed to have a characteristic strike-slip mechanism. Further north of the study region, earthquakes with focal depths > 40km are observed to originate along an extensional plane as evidenced by the observed normal fault plane solutions. We plan to further investigate these spatially varying trends and determine its role in segmentation along the Himalayas. We will also integrate results from various studies to discern the geodynamic evolution of the Sikkim Himalayas.

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AdriaArray seismic network – status in June 2023

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With the advent of plate tectonics in the last century, our understanding of the geological evolution of the Earth system improved essentially. The internal deformation and evolution of tectonic plates remain however poorly understood. This holds in particular for the Central Mediterranean: The formerly much larger Adriatic plate is recently consumed in tectonically active belts spanning at its western margin from Sicily, over the Apennines to the Alps and at its eastern margin from the Hellenides, Dinarides towards the Alps. It has been shown that data acquired by dense, regional seismic networks like AlpArray provide crucial information on seismically active faults as well as on the structure and deformation of the lithosphere. The Adriatic Plate and in particular its eastern margin have however not been covered by a homogeneous seismic network yet.

Here we report on the status of AdriaArray – a seismic experiment to cover the Adriatic Plate and its actively deforming margins by a dense broad-band seismic network. Within the AdriaArray region, currently about 990 permanent broad-band stations are operated by more than 40 institutions. In addition, 414 temporary stations from 24 mobile pools are deployed in the region achieving a coverage with an average station distance of 50 – 55 km. The experiment is based on intense cooperation between local network operators, mobile pool operators, field teams, and ORFEUS. Altogether, more than 50 institutions are participating in the AdriaArray experiment. We will report on the time schedule, participating institutions, mobile station pools, and maps of temporary station distribution.

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S17 - Posters - Structure and evolution of the lithosphere in the circum-Mediterranean

A new 3D model of the Ionian slab geometry and of the Central Mediterranean Moho

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The Central Mediterranean is a geodynamically complex area resulting from the interaction between the European and African plates. This process caused strong lateral variation in lithospheric thickness and thus strong variation in the Moho topography.
In this work we propose a new 3D Moho map for the Central Mediterranean, obtained from the interpolation of different data as: 2D velocity models (Scarascia et al., 1994; Chironi et al., 2000; Nicolich et al., 2000; Cassinis et al., 2005; Dellong et al., 2018; Agius et al., 2022), gravimetric profiles (Chironi et al., 2000; Dellong et al., 2018) and interpreted seismic reflection profile (Finetti et al., 2005; Civile et al., 2008; Catalano et al., 2013; Fedorik et al., 2018; Tugend et al., 2019; Sulli et al., 2021).
In order to optimize the geometry of the Ionian slab, we used the hypocenters of the seismic events extrapolated from different databases. In particular, we collected relocated seismic events from 1981 to the present.
We obtained a new constrained 3D Moho map for the Central Mediterranean that presents a strong lateral variation. Furthermore, the Ionian slab is quite different with respect to the model proposed by DISS (2021) and its geometry has been adapted to the hypocenters of the deepest seismic events (>40 km deep). In particular it was verticalized starting from about 200 km depth and the width was changed depending on new available data.
This model will allow a better understanding of the structure of the upper mantle and of the complex geodynamics of the area.

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S17 - Posters - Structure and evolution of the lithosphere in the circum-Mediterranean

Joint ambient noise and earthquake tomography of the Central Mediterranean region

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Surface wave tomography is a powerful tool for resolving crustal and upper mantle structures without the need of local sources. In this study, we present a 3D model of the Southern Italy and Central Mediterranean region based on the joint inversion of ambient noise and earthquake data. The input data consists of 11 900 phase velocity dispersion curves between 2 and 100 seconds obtained from ambient noise cross correlations and 81 000 phase velocity curves between 8 and 250 seconds obtained from averaging earthquake measurements using the two-station method. The two quality controlled datasets are merged using a correction factor that is derived from inter-station paths where both types of measurements are available.

Azimuthally anisotropic Rayleigh wave phase velocity maps are calculated using a regularized least square approach. The phase velocity maps are inverted for a 3D model by applying a stochastic particle swarm optimization algorithm.

The resulting 3D velocity model reveals several important features of the subsurface structure, including the subducted Calabrian and Hellenic slabs as well as a slab tear beneath Sicily. Moreover, the model images for example the transition from the Ionian Lithosphere to the Calabrian Slab, deformation of the Adriatic Lithosphere and aesthenospheric flow beneath the Tyrrhenian Sea. These results provide valuable insights into the evolution of the subduction zones in the Adriatic and Central Mediterranean region.

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S17 - Posters - Structure and evolution of the lithosphere in the circum-Mediterranean

Relative contribution of the Hellenic slab rollback and movement of North Anatolian Fault to the deformation in the Western Anatolia

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The Aegean Sea and western Anatolian peninsula are allocated at a widely spread active tectonic deformation zone that has primarily been controlled by the African plate subduction beneath the Hellenic Trench and the movement of the North Anatolian Fault Zone (NAFZ). The Mw7.0 2020 Samos earthquake, for instance, is an expression of the N-S directed extensional tectonic regime developed in response to African slab rollback movement in this region. A proper assessment of tectonic deformation process and its potential seismic hazard require a quantitative understanding of the contribution from the Hellenic subduction and the NAFZ to the surface movement. Here, we analyze the published regional GPS data along Greece-Turkey region to separate those contributions. Using a simple elastic-viscoelastic layered earth model, we first estimate the NAFZ contribution to the GPS velocity at each station with a varying slip rate. Then, we invert residual velocities obtained by subtracting the calculated velocity from the observed data, to derive subduction rate along the Hellenic trench. In the calculation, we assume the elastic thickness of 60 km based on the regional seismic tomography results. Our model results suggest 35 mm/yr of optimum slip rate of identifying the NAFZ, and ~40 mm/yr of the average subduction rate for the Hellenic Trench. The synthetic velocities can explain the observed GPS velocity within an average misfit of 2-3 mm/yr. Our results mean that the Hellenic slab rollback and the NAFZ movement are essential for the observed deformation beneath this region.

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Strain partitioning in SE Spain. Insights from cGNSS data

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We present continuous GNSS data (cGNSS) from SE Spain. We use in this work a total of 11 cGNSS stations located in the Murcia and Valencia regions (ALBA, UTIE, AYOR, VCIA, JUMA, ALCO, DENI, MCIA, CARG, SALI, and TORR). From the site position time series we obtained absolute velocity vectors. To discuss the meaning of this vectors in terms of present deformation, we calculated residual velocity field with respect the mean of two of the stations of our network (ALBA and AYOR). Furthermore, we also projected the residual velocity vectors along the N070E and N340E directions, i.e., sub-parallel and sub-perpendicular to the regional maximum shortening direction.

Our results indicate that the southernmost part of SE Spain (Murcia coast) is presently undergoing a shortening rate of 1.23±0.04 mm/yr along the N340W direction (CARG and MCIA stations). Only one major active fault has been defined in this area (Carrascoy Fault). This fault accommodates 0.7±0.2 mm/yr of N340W shortening. Therefore, the rest of our computed shortening (ca. 0.5 mm/yr) must be accommodated out of this structure.

In the northeastern part of SE Spain, the comparison between coastal stations (DEN, VCIA) and inland stations (ALCO and AYOR) indicates 0.90±0.06 mm/yr of NE-SW extension. No major active fault has been previously described in this area.

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S17 - Posters - Structure and evolution of the lithosphere in the circum-Mediterranean

Regional Geodynamic implications of new GNSS data from the Central Betic Cordillera

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We present GNSS data from a survey-mode network located in the Central Betic Cordillera. The Betic Cordillera is a collisional orogen, presently undergoing NNW-SSE shortening, as it is located in the convergence limit between Nubia and Eurasia Plates. Our GNSS network includes seven stations along a ca. 170 km long NE-SW striking profile. For these stations we calculated GNSS velocities from position time series. Then we calculated residual velocities with respect to a fixed Eurasia (ITRF2014 plate motion model(Altamimi et al., 2017)'}" id="614029728">). To discuss our data in terms of regional geodynamic implications we projected the velocity vectors along the N060E direction.

The absolute value of the N060E component of the obtained vectors shows a general increase of velocity from NE to SW, pointing to a regional NE-SW extension. This is in good agreement with previously reported data. Our data permit us to quantify an extension rate of 2.0±0.3 mm/yr. Furthermore, we also quantify the strain partitioning within the Central Betic Cordillera, including the Guadix-Baza and the Granada basins areas of high extensional rates, separated by a low-deformed crustal horst.

Therefore, the Central Betic Cordillera is an area undergoing 2.0±0.3 mm/yr of NE-SW extension within a collisional orogen. Furthermore, this area presents the highest topographic relive of the entire cordillera and an overthickenedcrust. We thus postulate that the extension quantified by our GNSS data could partially be the consequence of upper crustal extension related to gravitational instability. This instability would be produced by the overthickened crust.

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Deep subduction versus collision cessation: The fate of continental collisional orogens

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The contrasting fates of continental collisional orogens, i.e., deep subduction or collision cessation, are widely recognized by petrological, paleomagnetic and geophysical observations. However, the mechanisms of such different collisional modes, especially the dynamics of continental deep subduction, are controversial. In this study, we integrate the phase transition-induced density evolution into a thermo-mechanical numerical model. Combing the systematic petrological-thermo-mechanical models with force balance analyses, we find that the favorable conditions of continental deep subduction include high metamorphic transformation degree, mildly depleted mantle composition of the subcontinental lithosphere, long preceding oceanic slab, as well as the rheologically weak continental crust and asthenospheric mantle. Otherwise, the collision cessation mode is favored. The further calculations of slab negative buoyancy indicate that the phase transition-induced metamorphic densification of the subducted continental crust and mildly to moderately depleted continental lithospheric mantle can provide a great slab pull force to sustain the self-driven continental deep subduction; however, the positive buoyancy of highly depleted Archean lithospheric mantle impedes deep subduction and causes collision cessation. Based on these systematic numerical models, we also evaluate the crustal mass balance or deficit in continental collisional system, which indicates that a large amount of felsic crust can be subducted deeply with the sinking slab in the regime of continental subduction. In contrast, the recycled felsic crust is negligible in the regime of collision cessation. Thus, the different modes of continental collision play a crucial role in the global crustal recycling and related mantle heterogeneities.

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subduction. In contrast, the recycled felsic crust is negligible in the regime of collision cessation. Thus, the different modes of continental collision play a crucial role in the global crustal recycling and related mantle heterogeneities.

S18 - Posters - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

The density, temperature, and composition of Antarctic lithosphere constrained by gravity inversion and seismic tomography

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Spatial heterogeneities of density, temperature, and composition in the Antarctic lithosphere are crucial for controlling its geodynamic evolution and ice sheet dynamics. Mantle density and temperature can be estimated from seismic tomography models with a given or assumed mantle composition. However, this conversion is non-unique, as the mantle composition cannot be determined from seismic tomography alone.

Here, we used gravity inversion along with a seismic tomography model to constrain the composition of Antarctic lithosphere. We modelled lithospheric density distribution using a 3D finite element gravity inversion approach based on the esys-escript model in python. We derived a correction to an initial density distribution based on a seismic tomography model (ANT-20) with an initial uniform mantle composition. From the resulting density distribution and the initial seismic velocity distribution, we updated mantle temperature and composition and calculated the lithosphere thickness, mantle viscosity, and geothermal heat flow.

Our result highlights the compositional effect is essential to constraining the mantle temperature in East Antarctica, where our model suggests a highly depleted cratonic mantle in central East Antarctica. When compositional variations are considered, modelled mantle temperature increases in depleted regions by up to 150 °C to accommodate lower density and fast seismic velocity. Sensitivity tests suggest anelasticity effects dominate the uncertainty in resolving mantle temperature in slow seismic velocity regions (for example, West Antarctica). Future work requires constraining the seismic anelasticity to reduce the uncertainties in estimating lithosphere properties in West Antarctica.

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Use of ocean tide loading deformation to constrain tomographic models of the Earth

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Ocean tides periodically load Earth's surface and thereby introduce deformations. Despite being small in amplitude, surface deformations caused by the strongest tidal constituents can be reliably extracted from GPS data. The resulting signals are sensitive to the material properties of the Earth's interior across a broad range of spatial and temporal scales. This makes it a useful and potentially unique source of information about the planet's response at low frequencies and is complementary to models of the Earth inferred from seismic data. Although the latter is commonly used to constrain Earth's interior, short-period seismic waves are generally insensitive to density. In contrast, previous research indicates that the ocean tide load (OTL) surface displacements may be sensitive to both the elastic properties of the interior as well as to the mass distribution in the lithosphere and, perhaps, the upper parts of the mantle. Comparisons between observed OTL surface displacements and corresponding modelled responses for a suite of 1D reference models yields residuals of up to 0.3 mm (Martens et al., 2016). Regional-scale spatial coherency in the residuals suggests sensitivity to relatively long-wavelength deviations from the globally-averaged Earth structure. By resorting to a finite-element method to solve the 3D elastostatic momentum equation, we investigate whether part of these discrepancies can be explained by 3D structure that are in global tomographic models. The validation of current seismic tomographic models against independent geodetic observables (GPS data) represents a first step towards the self-consistent integration of geodetic and seismic data to image Earth’s crust and mantle.

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Travel time seismic tomography for the seismic stratigraphic interpretation of the crust at Coca river, Ecuador

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The San Rafael waterfall sinkhole on the Coca River in February 2020 caused by soil erosion raises the question of the stability of the knickpoint structure. The main objective of this research is to obtain tomographic images to interpret the seismic stratigraphic profile around the San Rafael knickpoint using seismic tomography. We use data from fourteen seismic stations of the permanent Ecuadorian seismic network in the region. The tomography results for the vertical cross-section P-wave velocity model show the geological formations and their transition to volcanic deposits. It also shows a structure with a high P-wave velocity value directly below the knickpoint. In contrast, the horizontal cross-section shows the structure of the extension of the volcanic deposits. The relative P-wave velocity shows a volumetric structure below the last pyroclastic deposits generated by the Reventador. The dimensions and characteristic velocity of the anomaly allow us to relate it to an igneous intrusion similar to the granodioritic intrusions known to the east of the volcano cone. Therefore, the presence of this pluton should condition the stability of the Coca riverbed, its slopes, and cliffs. The volcanic deposits in direct contact with the intrusion are suspected to be poorly consolidated. The P-wave velocity model shows that these volcanic deposits have an extension of 40 km. Greater stability is expected upstream of the San Rafael pluton. The relocation obtained by tomography also allows for defining the possible magmatic feeding system of the Reventador volcano.

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The lithospheric structure of the South China Sea indicated by 3D gravity modelling

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The density structure of the oceanic lithosphere of South China Sea (SCS) is key for understanding how the Hainan Plume affected the opening of the SCS. A lithosphere-scale 3-D density structural model has been constructed. We obtain the 3-D density structure of the sediments and the crust from regional reflection and refraction seismic lines. The temperature and related density structures of the mantle between 50 and 250 km are derived from a shear wave velocity (Vs) tomography model. To assess the density between the Moho and 50-km depth, we combine forward and inverse 3-D gravity modeling…

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S18 - Posters - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

Crustal structure and tectonics of the Achankovil shear zone, Southern Granulite Terrain, India using integrated multidisciplinary geoscientific data

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A comprehensive analysis of the character, formation, and exhumation of continental crust is studied using seismic reflection profiling across the Achankovil shear zone, Southern Granulite Terrain, India, one of the constituents of the 2000 km long East African orogen. Seismic imaging reveals a dipping reflection fabric extending from the surface to 60 km depth. We interpret the structure developed during the subduction-accretion-suturing of the Madurai and Trivandrum blocks. The deep-seated reflection fabric suggests a rheologically strong lower crust, as viscosity did not change much downwards due to the presence of mafic minerals and granulites in place of quartz and feldspars. Gravity modeling along seismic profile indicated density (velocity) perturbation in the form of high and low intrusive bodies of varying composition in the upper crust. The subduction zone environment might be responsible for the formation of ultramafic rocks comprising dunite, glimmerrite, and spinellite minerals in the region. Charnockites (granulites), the orthopyroxene (hypersthene) bearing anhydrous rocks of granitic composition that are formed at P-T condition between 5-12 Kbars and 700-1040^0 C are exposed on the surface. The ultra-high temperature metamorphic rocks provided insights into crustal dynamics and crust-mantle interaction. Seismic and gravity results are integrated with LVZ at 120 km depth derived from tomographic study, high mantle heat flow data, and various rocks/minerals such as sapphirine, humite bearing marbles, alkaline rocks, arc-related magmatism to understand the structure, composition, and thermal state of the lithosphere.

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S18 - Posters - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

3D Travel time tomography of the Gulf of Lion into the Ligurian Sea

DOI: 10.57757/IUGG23-1633 - LINK

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The Ligurian Sea is located in a complex tectonic area, at the Western Alps – Northern Apennines junction. Little is known about the structure of the basin and the continuation of the Alpine orogen offshore. The Ligurian Sea formed as a back-arc basin related to the retreat of the Apennine subduction zone. During extension, the Corsica-Sardinia block drifted eastwards, rotating counter-clockwise to its current position. The nature of the crust in the basin, whether atypical oceanic crust, thinned continental crust, or even exhumed mantle with thick sediment cover, is still a topic of debate. If oceanic crust was formed, its extent is poorly mapped.

Moreover, seismic and geodetic data show that the basin is now under compression. The area is known to have hosted large, tsunamigenic earthquakes in the past, however, its location boarding France, Monaco, and Italy, and climate mean that the coastline is densely populated despite the risk. Understanding the nature of the tectonics in the basin can therefore help assess the seismic hazard of the area.

In this project we use P-wave travel time tomography to generate a 3D velocity model of a section of the Gulf of Lion into the Ligurian Sea. This project is part of the DFG Priority Program "Mountain Building Processes in Four Dimensions (4DMB)". We use data from the LOBSTER-AlpArray OBS as well as from the 2006 SARDINIA Experiment. With FMTOMO we incorporate reflected and refracted rays as well as water multiples which in some cases improves the ray coverage.

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S18 - Posters - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

Cenozoic evolution and 3d geometry of the Senegal marine (onshore-offshore): Facies sedimentology, sequence stratigraphy

DOI: 10.57757/IUGG23-4983 - LINK

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[2]*Universite cheikh anta diop, Geologie, dakar, Senegal*

This study aims to build a 3D stratigraphic database based on the correlation of boreholes with logs and seismic reflection lines calibrated in terms of age, lithology, and environment. The aim of this study is to build a 3D stratigraphic database based on the correlation of logging wells and analysis of seismic reflection lines calibrated in age, lithology, and sedimentation environment from previous borehole wells. The MSBGC basin has been intensively prospected for hydrocarbons since the 1950s, both onshore and offshore. Extensive seismic reflection, gravity, magnetic and well data are available. Since 2014, major discoveries have been made in offshore Senegal, prompting interest in conducting a predictive study from offshore to onshore to identify possible continuities between the environments.

Results from the lithostratigraphic investigations we undertook show a mitigated offshore-onshore correlation. This is probably due to the size of the area, the scattered wells or the geological and tectonic phenomena that have affected the basin.

Petrophysical analyses obtained on some wells show that the Maastrichtian reservoirs are made up of sandstone, sandstone sand, and clayey sand. This is probably due to the major regression that occurred in the Upper Maestrichtian, which is expressed in the overlying sandstone deposits found in most wells. Maestrichtian has excellent reservoir properties with average porosities of at least 28% and high permeabilities with clay volumes below 50%.

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S18 - Posters - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

The Collaborative Seismic Earth Model: Generation 2

DOI: 10.57757/IUGG23-1818 - LINK

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We present the second generation of the Collaborative Seismic Earth Model (CSEM), a multi-scale global tomographic Earth model that continuously evolves via successive regional and global-scale refinements. Harvesting the distributed human and computation power across the tomography community, the CSEM framework allows to systematically build on previously accumulated knowledge. This is achieved by providing the current version of the CSEM as a starting model for regional tomographic studies and incorporating these findings into the following version of the CSEM.

The CSEM hosts 21 refinements from full seismic waveform inversion with diverse regional scales ranging from hundreds of km to entire continents. Noticeable changes since the first generation include detailed local updates for the Central Andes, Iran, South-east Asia, and the Western US, and continental scale refinements for Africa and Asia. A global long-period model improves the resolution int areas that have not been covered by other refinements. The current CSEM combines three-component waveform data from 1,637 events and over 700,000 unique source-receiver pairs across all regional updates.

To complete the model, we perform a global full waveform inversion over multiple period bands to a minimum period of 50 s. With this approach we ensure waveform prediction across regional model boundaries and that the resolved Earth structure is part of a single coherent model. We demonstrate seismic waveform prediction of minimum periods of 50 s on the global scale and for 20 s to 30 s in selected areas. Active participation in the project is encouraged.

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S18 - Posters - Integrating Seismic Tomography With Mineral Physics and Potential Fields to Describe the Crust and Upper Mantle Physical State

Underplating evidence on Mejillones Peninsula zone, Chile

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Mejillones peninsula located in the north of Chile is considered a potential seismic barrier. Two major earthquakes have occurred south and north of it: The M8.1 1995 Antofagasta and the M7.8 2007 Tocopilla earthquakes. Slip and aftershock distribution show the central axis of this peninsula as the limit. We use travel time data of earthquakes recovered by three networks, overlapping in space but not in time, including offshore stations (CINCA network 1995; TaskForce 2007, and MEJIPE 2013-2015). A three-dimensional local tomographic inversion was performed using ~4000 events. The resolution of tomographic images was analysed by the model resolution matrix and numerical tests. Vp velocity and Vp/Vs ratio images are capable of resolving main tectonic units up to 80 km depth. Our work shows the presence of two basal possible underplating structures: The first is located below the peninsula with similar dimensions of it (~60 km) found at depths > 35 km and a second structure of smaller dimensions is located to the north where the Tocopilla earthquake nucleated. This evidence justifies the possible segmentation in the rupture zones of both earthquakes in the north of Chile.

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S19 - Posters - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Seismic anisotropic parameters of the Northwest Himalaya from splitting measurements of core refracted shear wave (SKS) phases

DOI: 10.57757/IUGG23-3961 - LINK

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The Himalaya as the type example of continental collisional orogeny has resulted from the convergence between the Indian lithosphere and the Eurasian lithosphere. Recent enhancement in broadband instrumentation in the northwest Himalaya (Jammu and Kashmir or J&K) provides an unprecedented dataset to study the deformation due to the Indo-Eurasia convergence. The main tectonic feature in the J&K Himalaya is the intermontane Kashmir basin. The Kashmir basin occurs in between the rupture zones of two historic earthquakes and hence is referred to as the "Kashmir seismic gap". We determine azimuthal seismic anisotropy using core refracted shear waves (SKS) and interpret the results to develop insight into the prevailing geodynamics of the region. We use data from the J&K Seismological NETwork (JAKSNET), operational between 2013 and 2022, which consisted of 24 broadband seismograph stations. The network extends across the Himalayan arc from the Siwalik (S), Lesser, Greater, and the Tethyan Himalaya (N), and along the arc from Jammu-Kishtwar (E) to the Kashmir Valley (W). Seismic data from 427 earthquakes (Mw>=5.5), within an epicentral distance range of 85°-135°, are selected and provide good azimuthal coverage for most stations. Specifically, we will present individual station measurements of splitting parameters, and the lateral variation of anisotropy and consider whether the anisotropy signatures are likely to have arisen from pre-collision or present day deformation. By correlating anisotropic parameters with geodetic and long-term geologic measurements we aim to understand the relationship between upper crustal deformation and the mantle flow field.

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S19 - Posters - Fabrics and Dynamics of the Lithosphere-Asthenosphohere System Imaged by Seismic Anisotropy and Integrated Studies

Mantle anisotropy from shear-wave splitting along the Bohemian Massif-Eastern Alps north-south transect

DOI: 10.57757/IUGG23-1690 - LINK

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Splitting of shear waves is considered to be evidence of their propagation through an anisotropic medium. We evaluated splitting parameters of core-mantle refracted shear waves (SKS) along with their particle motions (PM), recorded during the passive seismic experiments AlpArray-EASI (2014-2015) and the AlpArray Seismic Network (2016-2019). The study area covers the western part of the Bohemian Massif and the Eastern Alps in about 200 km broad NS-oriented transect. Careful signal preprocessing includes several steps: automated identification of SKS waveforms, filtering and quality check. Special attention is paid to checking the geographical orientation of seismometers at all stations. Parameters of anisotropy – shear-wave split delay time and direction of the fast split shear waves in the LQT coordinate system are evaluated in 3D by two modified splitting methods, the eigenvalue and the transverse energy methods. To improve the splitting analysis results, we also include so-called null splits, i.e., results for directions where SKS waves do not split or their splitting is close to null. In the case of waveforms with a low signal-to-noise ratio (SNR) we apply a more robust PM method. The modified version of splitting methods (Vecsey et al., 2008) allows us to retrieve the 3D orientation of large-scale anisotropic structures in domains of the mantle lithosphere and to detect abrupt changes of their fabrics as well as present-day deformations within the sub-lithospheric part of the upper mantle.

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Geodynamic implications for the crustal and upper mantle anisotropy beneath the North China Craton

DOI: 10.57757/IUGG23-0758 - LINK

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[3]*China University of Geosciences, School of Geophysics and Information Technology, Beijing, China*

The North China Craton (NCC) is one of the oldest craton in the world. Since the Cenozoic, the NCC has experienced strong lithospheric thinning, accompanied by extensive tectonic deformation and volcanic activities. To better constrain the geodynamic processes and mechanisms of the lithospheric deformation, we used a linear damped least squares method to inverse simultaneously Rayleigh wave phase velocity and azimuthal anisotropy at periods of 10-80 s with teleseismic data recorded by 388 permanent stations in the NCC and its adjacent areas. The results reveal that the anomalies of Rayleigh wave phase velocity and azimuthal anisotropy are in good agreement with the tectonic domains in the NCC. The whole lithosphere of the Ordos block shows a high-phase velocity and rotated fast axis, which is related to the well-preserved thick lithospheric root and counterclockwise rotation of the Ordos block. The horizontal extension of the upwelling materials within the lower crust under the Datong volcano contributes to the regional rotation pattern of the fast axis direction of Rayleigh wave together with a distinct low-velocity anomaly. A NW-SE trending azimuthal anisotropy and a low-velocity anomaly originated from the Datong volcano at atop of the asthenosphere are revealed to be subparallel to the Zhangbo fault zone. This observation may be caused by the upwelling magma of the Datong volcano flow into the asthenosphere of the eastern NCC, which also provides new insights into the understanding of the lithospheric thinning of the eastern NCC.

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The velocity structure and crustal anisotropy in the lithosphere-asthenosphere system of the Himalayan orogen and its adjacent areas

DOI: 10.57757/IUGG23-1451 - LINK

Xuemei Zhang[1], Zhigao Yang[2], Yihai Yang[3], Guangbao Du[2], Wen Yang[4], Haixia Shi[4], Liye Zou[1], Jie Liu[4]
[1]China Earthquake Networks Center, Seismic Networks Department, Beijing, China
[2]China Earthquake Networks Center, Early Warning Quick Report Department, Beijing, China
[3]Shaanxi Earthquake Agency, Shaanxi Earthquake Station, Xi'an, China
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Tethyan oceanic subduction, terrane accretion and continental collision of the Indian and Eurasian plates since 50Ma ago lead to the current Himalayan orogen. As imagined from geophysical data, the deep structure and anisotropy of the lithosphere-asthenosphere system provides important clues in understanding the modality of the orogenic convergence and collision. Based on the seismic data from CENC, IRIS and ISC, using surface wave tomography, we calculated the group velocity. Base on Metropolis rule, we improved the simulated annealing algorithm to simultaneously inverse the velocities and thicknesses and identified the Moho depth and the bottom of lithosphere. We computed receiver functions at permanent and portables stations to provide constrains for crustal deformation. A harmonic analysis was employed to investigate the accurate crustal anisotropy. Crustal shortening and thickening should have occurred beneath the study region. Its partial melting might have enhanced the crustal anisotropy and promoted the accumulation and release of strain. The Himalayan block (HM) is covered by a high velocity anomsaly of about 5% indicating a relatively thin asthenosphere with high velocity. The Vs models demonstrate the leading edge of the subducting Indian slab reaches up to Bangong-Nujiang suture belt (BNS). It indicated that the crust with the thickness of about 65 km in HM and the lithosphere (~160 km). The epicenters in HM is relatively deeper than that northern BNS, more deep focus earthquakes are located in the uppermost mantle. The study is supported by the Chinese National Science Foundation (41774069).

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S20 - Posters - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

Pan Canadian Narratives and Numbers: A Knowledge to Action Initiative in the Earthquake Early Warning Education (E3) Project

DOI: 10.57757/IUGG23-4668 - LINK

Shona Van Zijll De Jong[1], Yu-Yen Pan[2], Marie-Hélène Graveline[3], Glenn Dolphin[4]
[1]Queens University/ University of Calgary,
Department of Geological Sciences and Geological Engineering, Kingston, Canada
[2]Simon Fraser University, Department of Earth Sciences, Burnaby, Canada
[3]Université du Québec à Montréal, Institut des sciences de l'environnement, Montreal, Canada
[4]University of Calgary, Department of Geoscience, Calgary, Canada

Partnerships with Earth Science for Society, the Canadian Risk and Hazards Network, the Assembly of First Nations, the International Association of Emergency Managers, the Canadian Federation of Earth Sciences and others have been critical for reaching the target audience of the Pan Canadian bilingual E3 Survey. Research partners also circulated our 2022 article entitled *A new earthquake warning system will prepare Canada for dangerous shaking* and its key message:

"*About 10 million people live in Canada's earthquake-prone zones. Yet few have practical knowledge of what to do with new early warning system alerts which aim to save lives and protect livelihoods*" .

Importantly, such partnerships also provide the structure for the distribution of the E3 Survey final report.

The primary aim of this presentation is to outline how our partners have helped us to research and report on three questions of national interest:

- What connects Canadian science education, earthquake literacy and time/space specific skills required to succeed in earthquake prone locations ?
- How do Canadians build their earthquake literacy?
- Why does Canada needs earthquake literacy taught in disaster risk management activities and programs?

We showcase how the Knowledge to Action Framework analysis of E3 Survey results reveals multiple aspects of E3 delivery that need to change. We suggest that with evidence based recommendations, our partners can identify resource needs and pinpoint future interventions. Overall, we conclude that investment in future E3 products – via digital delivery - may revolutionize E3 geoliteracy levels and close the E3 Knowledge to Action gap.

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S20 - Posters - Education & Outreach to Ensure Success of Earthquake Early Warning Programmes

Envisioning E3 Futures at the Seismic Science-Society Interface: Preliminary Analysis of the Pan Canadian Bilingual E3 Survey

DOI: 10.57757/IUGG23-4690 - LINK

Shona Van Zijll De Jong[1], *Marie-Hélène Graveline*[2], *Glenn Dolphin*[3]
[1]*Queens University/ University of Calgary,*
Department of Geological Sciences and Geological Engineering, Kingston, Canada
[2]*Université du Québec à Montréal, Institut des sciences de l'environnement, Montreal, Canada*
[3]*University of Calgary, Geoscience Department, Calgary, Canada*

The theme of the University of Calgary Natural Resources Canada (NRCan) funded project is: *Addressing misconceptions around magnitude and intensity to inform earthquake early warning (EEW) alerting strategies*

Last year, the Earthquake Early Warning Education (E3) socio cultural research project began. The E3 project has a dual purpose: to promote debate on the issues shaping Canadian earthquake risk management; and, to reflect on the biases in the media that reports on earthquakes. As seismic science - societal risk educators, we represent scholarship from across the spectrum (natural sciences, social sciences, and humanities). The E3 socio cultural project allows us to look ahead. We consider the contemporary and historical processes that shape how Canada will do E3 once the NRCan EEW is implemented in 2024.

This presentation provides a preliminary report on the Pan Canadian bilingual E3 Survey results.

Survey participants responses were needed to reveal the challenges this project faces. As a result, we have been provided with insights into the Canadian seismic science-society interface; and, the challenges this project faces. The E3 survey results will continue to make an impact both in Canadian E3 and in the training of future disaster risk management (DRM) practitioners.

The E3 socio cultural project is an opportunity to talk about how Canada might use existing tools, perspectives, social media, and DRM training sessions to effectively support the NRCan EEW in 2024 and beyond.

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JA01a - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Generative adversarial networks as a fast surrogate model for simulations

DOI: 10.57757/IUGG23-4913 - LINK

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[1]*Massey University, College of Sciences, Palmerston North, New Zealand*
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The complexity and level of detail in numerical models for geosciences have increased as computational power has become more available and parallelism and new computational techniques have reduced the computational burden of numerical modelling. However simulations still pose a large computational challenge where a large number of simulations are required to adequately sample the input space. One approach to alleviating these limitations is through construction of a surrogate model. A surrogate (or metamodel) is a model of the simulation results within a defined parameter space. Surrogate models typically learn from simulation results to create a fast approximation to the numerical model. We have been using Generative Adversarial Networks (GAN's) as a surrogate model to depth-averaged simulations of debris avalanches at Ruapehu volcano, New Zealand. This GAN appears highly successful, creating inundation outlines of volcanic debris avalanches (VDA) with high precision (>90% similarity to simulations in some cases) and more than 130,000 times faster than VDA simulations. Our trials of GANs so far highlight a few key points: (1) well-trained GAN surrogates have high accuracy in reproducing model footprints, (2) the surrogate GANs show better accuracy when constrained to groups with similar simulation inputs (i.e. it is not generalizable), and (3) different loss functions (mean-square error vs. mean absolute error) affect trainability and accuracy. These results, and our attempts to push the limits of GAN's to problems that consider time-varying inputs, such as bushfire spread, will be highlighted.

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JA01a - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Addressing bias in predictions of global sedimentation rates through physical parameters, few-shot learning, and numerical modeling

DOI: 10.57757/IUGG23-4227 - LINK

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[2]University of Kiel, Institute of Mathematics, Kiel, Germany
[3]MARUM: Centre for Marine Environmental Science, Paleoceanography, Bremen, Germany
[4]University of Kiel, Insitute of Mathematics, Kiel, Germany

The prediction of global sedimentation rates is a critical aspect of comprehending various phenomena, such as carbon sequestration and seafloor stability. With the advent of machine learning, there has been an increasing trend towards utilizing these techniques to predict quantities on the seafloor, including porosity and total organic carbon. Several studies have been conducted to predict sedimentation rates[cm/ka] and mass accumulation rates[Mt/yr] using techniques such as k Nearest Neighbors and neural networks. However, a significant issue with these methods is the observed tendency for the models to over-predict sediment budget, a crucial parameter in evaluating the validity of predictions. This bias may stem from the paucity of low sedimentation rate data points on the continental shelves, where most scientific expeditions concentrate on high sedimentation rate areas. This bias disregards valuable data on low sedimentation rates, which would be useful in developing a comprehensive global map of sedimentation rates. To address this issue, there are several potential methods. The first involves identifying physical parameters, such as porosity, sediment grain size and bottom currents, that correlate with low sedimentation rates and can be utilized to identify these areas. The second involves utilizing few-shot learning, a machine learning technique that allows for training with limited low sedimentation rate labels. The third method involves the use of numerical models in small spatial areas, which can offer further insights into the processes behind low sedimentation rates and provide more data for analysis.

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JA01a - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Investigating the role of auxiliary and texture features for improving flood detection with interpretable machine learning

DOI: 10.57757/IUGG23-3333 - LINK

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[3]*Luxembourg Institute of Science and Technology, Environmental Research and Innovation, Esch-Sur-Alzette, Luxembourg*

Access to big data in remote sensing, deep learning and machine learning models, along with good computational power has improved the accuracy for flood mapping. However, the reasons for this improved classification performance for such models, still remain largely unexplored. In this study, we explore the use of Sentinel-1 synthetic aperture radar (SAR) data and auxiliary layers for flood detection, with a focus on identifying the most important features for accurate classification. In addition to the pre- and post-event SAR layers, the auxiliary layers used in this study include topography, permanent water, and land-use land cover, along with SAR texture layers for binary flood inundation classification. Random forest model was tested for four completely different flood events characterized by notable differences in land-use, flood magnitude, and elevation patterns. Several scenarios were constructed to evaluate which input features contributed the most to the identification of an appropriate decision boundary for the classification. The contribution of the input features to model performance was explored using permutation feature importance. Our results demonstrate that SAR data, along with the auxiliary layers, can effectively identify flooded areas with high accuracy. Among the auxiliary data selected, the feature importance analysis shows that the topography plays a more important role than permanent water and land-use landcover for flood delineation.

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JA01a - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

FAIR shallow landslide hazard mapping

DOI: 10.57757/IUGG23-3255 - LINK

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A single triggering event such as strong precipitation, may result in swarms of shallow landslides that cumulatively pose significant risks to population, infrastructure and the environment. There is large scientific and societal interest in hazard maps that display the susceptibility to shallow landslide occurrence while accounting for spatio-temporal variability of triggers and influencing factors. In this study, we implemented a generic and scalable hazard mapping workflow in accordance with the FAIR principles that relies on a Random Forest Classifier. It is a purely data-driven approach which due to its modular implementation allows a flexible adaptation to different areas of interest and integrated data. It's application results in individualized and reproducible hazard maps. The validation of these maps as well as the underlying workflow is considered as well. The workflow facilitates dynamic hazard maps of varying temporal scope. This temporal dynamic is achieved through the integration of highly volatile features such as precipitation events. In this way, hazard maps can be created depending on the weather forecast. Geohazard potential changes dramatically in response to volatile triggering conditions making their inclusion into the mapping process a natural extension to the established static hazard mapping features. First results of enriching data-driven landslide hazard mapping with temporal data are promising. The resulting temporally dynamic hazard maps offer a wide range of opportunities to improve landslide risk management.

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JA01a - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Road conditions analysis and forecasting in Arctic: multi-source machine learning approach

DOI: 10.57757/IUGG23-2849 - LINK

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Climate change, global warming, and increasing weather extremes, especially in Sub-Arctic and Arctic regions with unusual freeze-thaw cycles, can cause more and more challenges to the infrastructure such as road networks. The maintenance and repair of road network can be time consuming and expensive. Better targeted and proactively planned maintenance could have economical benefits and increase the safeness of the roads. To tackle this, artificial intelligence (AI) and machine learning (ML) techniques with the availability of digitalised diverse historical and real-time data, can be utilised, on one hand, to better understand the causes of the thaw damages and frost heave affecting the roads, and on the other hand, to build more advanced forecasting models for short- and long-term road conditions and thaw damage risks. In this work, as a first step, for building data-driven ML approaches to Arctic road damage forecasting, the possibilities of applying different multi-source are analysed. To this end, we are applying multi-source data sets of historical weather observations, in situ and mobile measurements of road surface and ground, and response variables of thaw damage and road wearing. As a result, we are showing 1) the benefits of different data sources using explanatory analysis, 2) the importance of different observations explaining the road conditions, and 3) the guideline of building explainable AI and ML approaches to combine digitalised information to forecast road conditions such as the thaw damage probability on road network in Northern Finland.

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JA01b - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

BRDF/Albedo Retrievals using Unsupervised Segmentation in the Arctic in the context of NASA ARCSIX

DOI: 10.57757/IUGG23-2059 - LINK

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Since the late 1990s, NASA's Earth Observing System constellation of satellites has provided continuous, long-term observations of atmospheric and surface processes on Earth including surface albedo and Bidirectional Reflectance Distribution Function (BRDF) that are generated as an operational product using cloud-cleared, multi-angle surface reflectances over the course of several days. The BRDF is central to imagery-based cloud and aerosol retrievals, while the surface albedo is a fundamental Earth energy budget parameter. Yet, this product is currently unavailable at higher latitudes where (1) the low contrast between clouds and sea ice/snow poses a challenge for cloud clearing, and (2) drifting ice floes are not accounted for, resulting in a significant gap in our understanding of the Arctic radiation budget.

To address this gap, we propose the development of a BRDF/albedo product for moving sea ice floes and snow called the Sea Ice Floe and Snow Albedo Tracker (SIF-SAT). By leveraging multi-overpass, multi-angular satellite data, SIF-SAT will retrieve BRDF and albedo under low contrast and moving surface conditions. We combine existing cloud masks with machine learning (ML) models to produce cloud-cleared scenes in the Arctic. These scenes are then fed to a segmentation algorithm to identify individual sea ice floes and their reflectances are tracked over time to obtain BRDF and albedo. This presentation will primarily focus on the cloud-clearing model which has implications for radiation science in polar regions. SIF-SAT will enhance our capabilities in the Arctic and enable more accurate estimates of the cloud-radiative effect and ice-albedo feedback.

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JA01b - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Deep Learning-Aided High-Resolution Temporal Gravity Field Simulations: Monthly global mass grids and Spherical Harmonics from 1994 to 2021

DOI: 10.57757/IUGG23-4920 - LINK

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Starting from April 2002, Gravity Recovery and Climate Experiment (GRACE) and, its successor mission GRACE-FO (FollowOn) have provided irreplaceable data for monitoring mass variations within the hydrosphere, cryosphere, and oceans, and with unprecedented accuracy and resolution for over two decades. However, the long-term products of mass variations prior to GRACE-era may allow for a better understanding of spatiotemporal changes in climate-induced geophysical phenomena, including terrestrial water cycle, ice sheet and glacier mass balance, sea level change and ocean bottom pressure. In this study, total water storage anomalies (TWSA) are simulated/reconstructed globally at 1.0°x1.0° spatial and monthly temporal resolutions from January 1994 to December 2020 with an in-house developed hybrid Deep Learning (DL) architecture using GRACE/-FO mascon and SLR gravimetry, ECMWF Reanalysis-5 (ERA5) data. We validated our simulated mass change data products both over land and ocean, not only through mathematical performance metrics (internal validations) such as RMSE or NSE along with comparisons to previous studies, but also external validations with non-GRACE datasets such as El-Nino and La-Nina patterns, barystatic global mean sea level change, degree (d) 2 order (o) 1 spherical harmonic coefficients (C21, S21) retrieved from Earth orientation parameters, Greenland Ice sheet mass balance and in-situ Ocean Bottom Pressure measurements were carried out. The overall validations show that the proposed DL paradigm can efficiently simulate high-resolution monthly global gravity field both in GRACE/GRACE-FO and pre-GRACE era. The resulting simulated data products are available as monthly mass change grids as well as spherical harmonic models up to d/o 180.

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JA01b - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Regional ZTD Modeling by Using Multi-Source Data Based on Machine Learning: A Case Study of Severe Weather Event in Turkey

DOI: 10.57757/IUGG23-4023 - LINK

Selma Zengin Kazanci[1], *Bahadır Çelik*[1]
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Zenith tropospheric delay (ZTD) is critical information for global navigation satellite systems (GNSS) meteorology. ZTD is estimated from GNSS stations, radiosonde stations, meteorological stations, meteorological reanalysis data, global pressure and temperature 3 model (GPT3), etc. Extreme weather events can detect from ZTD values. In this situation, the importance of obtaining reliable ZTD data increases. With the development of machine learning, its usability has also been raised in ZTD estimation. In this study, we have developed three ZTD models based on the support vector machine model (SVM) using radiosonde ZTD data, the International GNSS Service (IGS)-ZTD products, ZTD estimated by European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA5) data throughout July 2017. The reason for choosing the year 2017 is the extreme weather events as severe precipitation and hail events that took place in Istanbul (IGS-ISTA) on July 18-27, 2017. In order to investigate which ZTD model gives better results, Root Mean Square Errors (RMSE), and bias were adopted for our comparisons in extreme weather events and normal weather conditions.

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JA01b - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Machine learning approach for automatic infrasound signal classification

DOI: 10.57757/IUGG23-2618 - LINK

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[2]*Research Centre for Astronomy and Earth Sciences- ELKH, Institute for Geological and Geochemical Research, Budapest, Hungary*

The huge volume of infrasound detections asks for machine learning techniques for the automatic classification of signals. Our objective was to assess machine learning algorithms in identifying signals. Since 2017, the Hungarian infrasound array has collected approximately one million detections, processed with the Progressive Multi Channel Correlation method. Of these, we categorised some 14,000 detections from quarry blasts, storms and a power plant. These detections constitute the dataset for machine learning training, validation and testing. After pre-processing, features were extracted from the waveforms both in the time and frequency domain, to characterize the physical properties of the signals. We also defined PMCC related features to measure the similarity between the detections. For training, two classifiers were selected, Random Forests and Support Vector Machines. Hyperparameter tuning was performed with three-fold cross-validation using grid search. As a metric, f1 score was selected, and the confusion matrices were analysed. The goal was to separate the detections labelled as quarry blasts from the storm and power plant classes. The results reach 0.88 f1 scores, and high true positive rate for the quarry blasts, which show promising step in the direction of infrasound signal classification via machine learning.

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JA01b - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

GNSS Time-series Denoising and Prediction through a Combined Use of Wavelet and Deep Learning. Testing on data-series from Campi Flegrei

DOI: 10.57757/IUGG23-3058 - LINK

Rolando Carbonari[1], *Rosa Di Maio*[2], *Umberto Riccardi*[2], *Prospero De Martino*[3], *Gianpaolo Cecere*[4]
[1]*The Hebrew University of Jerusalem, The Fredy & Nadine Herrmann Institute of Earth Sciences, Jerusalem, Israel*
[2]*Università degli Studi di Napoli Federico II, Dipartimento di Scienze della Terra- dell'Ambiente e delle Risorse, Napoli, Italy*
[3]*Istituto Nazionale di Geofisica e Vulcanologia INGV, Osservatorio Vesuviano, Napoli, Italy*
[4]*Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio di Grottaminarda - Centro Nazionale Terremoti, Grottaminarda, Italy*

The Global Navigation Satellite System (GNSS) is widely acknowledged for its ability to monitor ground deformation and provide guidance to assess associated hazards. However, noise in GNSS time-series can hide or even mask the actual ground deformation signals. Various denoising techniques have been developed to improve the signal-to-noise ratio and detect low amplitude signals. The Discrete Wavelet Transform (DWT) has proven to be one of the most effective techniques. However, the DWT requires extensive time-series data and it is therefore computationally expensive, making it unsuitable for real-time monitoring.

In this research, we first assess the feasibility of using deep learning (DL) to perform the equivalent of wavelet analysis on GNSS data. Secondly, we explore the possibility of using DL to predict the future values of a wavelet-denoised GNSS time-series. The proposed method can be described as follows: i) wavelet analysis is applied to GNSS time-series coming from different sites in a permanent network; ii) a DL model is trained using the original time-series as input and the "Wavelet processed" series as target; iii) the trained model is used to perform real-time denoising on newly recorded GNSS data; iv) a separate model is trained to predict future values of the so-denoised GNSS data.

We tested our approach on GNSS data collected in the Campi Flegrei area (Naples, Italy), an active volcanic caldera well-known for its ongoing deformation. The preliminary results are promising, as the models show good accuracy in both tasks: simulating past denoised signals and predicting future ones.

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JA01c - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Modeling of Nitric Oxide infrared radiative flux in lower thermosphere: A machine learning perspective

DOI: 10.57757/IUGG23-0791 - LINK

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Nitric oxide (NO) plays a crucial role in the energy budget and chemistry of the mesosphere and lower thermosphere (MLT). During geomagnetic storms, a massive amount of energy is deposited in the thermosphere. To balance this sudden increase of energy deposition, enhanced emission from NO has been observed in the thermosphere. So, an accurate prediction of Nitric Oxide radiative flux becomes vital to understanding the thermospheric behavior, especially during extreme space weather events. Due to the advancement in computation techniques, machine learning (ML) has become a valuable tool in space weather forecasting. The SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument on board the TIMED satellite provides continuous measurements of the radiated energy at 5.3 μm by NO since 2002. The availability of SABER data enables us to use machine learning for developing a data-driven machine learning model for Nitric Oxide Infrared Radiative Flux (NOIRF). Using machine learning, a predictive model (NOEMLM) is developed. The model is able to extract the underlying relationships between the input features and effectively predict the NOIRF. The model NOEMLM has outstanding performance for both the datasets training as well as testing. The model predictions have been verified by using the actual measurements of SABER. The NOEMLM predictions have good agreements with SABER observation during the geomagnetic storms and quiet time, which shows that the model can predict NOIRF during extreme space weather conditions with good accuracy.

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JA01c - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Testing a "fully – automated" clustering algorithm for stress inversions (CluStress)

DOI: 10.57757/IUGG23-4514 - LINK

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[2]Eötvös Loránd Research Network ELKH, Institute of Earth Physics and Space Science EPSS, Sopron, Hungary

The goal of this contribution is to present the "fully-automated" clustering algorithm developed by the authors. This is augmented by a case study where the authors carried out various cluster analyses of the focal mechanism solutions (FMS) estimated from local and teleseismic measurements and then performed stress inversions using the resulting clusters. This algorithm does not call for the setting of hyper-parameters by the users, thus greatly reducing the level of subjectivity introduced by user choice; the time required to finish the clustering can also be decreased. There is, however, an optional hyper-parameter which can be used for outlier detection, i.e. identify the data points considered to be noise in the input dataset, increasing the performance of the stress estimations.

For probing the efficiency of their algorithm, systematic series of tests were executed on synthetic FMS data featuring clusters of various characteristics. During these tests, CluStress has been compared to other established clustering methods, namely, hierarchical density-based clustering for applications with noise (HDBSCAN) and agglomerative hierarchical analysis. Quantitative metrics, mainly the characteristic curves produced using the so-called silhouette-coefficient indicate that CluStress generates the most robust clusters for the stress inversions on synthetic data.

A similar conclusion could be drawn from the same test performed using real FMS data of the investigated study area. As for this latter case, the resulting stress tensors show good agreement with the earlier published results with the notable exception of traces of extension, identified in some parts of the region after FMS clustering.

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JA01c - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Deep learning in spaceborne GNSS Reflectometry for Ocean Remote Sensing

DOI: 10.57757/IUGG23-3398 - LINK

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[1]*German Research Centre for Geosciences GFZ, Space Geodetic Techniques, Potsdam, Germany*
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GNSS Reflectometry (GNSS-R), referring to exploiting the GNSS signal of opportunity reflected off the Earth surface, has emerged as a novel remote sensing technique for monitoring geophysical parameters. The Cyclone GNSS (CYGNSS), launched on December 15th, 2016, is a constellation of eight microsatellites with cost-effected receivers, fully dedicated to the GNSS-R applications, and can track reflected signals from multiple GNSS satellites. Compared with traditional optical and radar remote sensing, GNSS-R can provide massive datasets with global coverage and improved temporal resolution, which offers unique potential for characterizing the complex Earth system.

With the increase of GNSS-R observation data volume, deep learning techniques show their strong capability in retrieving ocean surface wind speed by extracting features from the Delay-Doppler Maps (DDMs). Furthermore, it is shown that deep learning models significantly improve the quality of existing GNSS-R wind speed products. The model achieves an overall RMSE of 1.31 m/s compared with the ERA5 reanalysis data and leads to an improvement of 28% in comparison to the operational retrieval algorithm based on the empirical geophysical model functions (GMFs).

However, some known geophysical parameters, such as precipitation, are theorized to be impacting the reflected signals, altering the pattern of the DDMs, and consequently biasing the retrievals. The correction of such bias is not trivial because of its nonlinear dependency on various environmental and technical parameters. Therefore, we explore how deep learning-based fusion on additional precipitation data can correct the bias and further investigate the potential of deep learning models to retrieve precipitation.

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JA01c - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Gravity signal separation using a neural network

DOI: 10.57757/IUGG23-2909 - LINK

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[2]*Technical University of Munich, Professorship for Big Geospatial Data Management, München, Germany*

The Earth's gravity field varies temporally due to a multitude of geophysical processes involving mass displacements. These include processes in the areas of continental hydrology, glaciology, oceanography, atmosphere and solid Earth science. As a variation in the gravity field can be represented as the integral over all mass changes on Earth, temporal gravity measurements include the cumulative effect of the above-mentioned mass displacement processes. Interpreting the individual signal components included in such data and further using them, e.g. in order to constrain data-driven process models, requires a method to extract the signal of interest from the spatio-temporal gravity data.

The signal components to be separated differ by their spatial and temporal characteristics, which are in principle known from models or other measurements. We are aiming to exploit these different characteristics for extracting the individual signal components out of the full signal.

As neural networks are known to be powerful in pattern recognition tasks using image data, we transfer our signal separation task to an image-to-image translation task. A neural network is trained based on known signal patterns with the aim to extract individual signal components from their sum.

Although we use the updated ESA Earth System Model for gravity simulations for our method development, the results could be beneficial not only for signal separation in satellite gravity data but also for similar tasks in other geospatial datasets representing the sum of multiple signal components.

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JA01d - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Forecasting geomagnetic storm disturbances and their uncertainties using deep learning

DOI: 10.57757/IUGG23-3437 - LINK

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[4]Observatori de l'Ebre, Experimental department, Roquetes, Spain

Severe Space Weather (SW) activity produced by geomagnetic solar storms gives rise to harmful geomagnetically induced currents (GICs) flowing on technological systems, thus potentially threatening the critical infrastructures on Earth. The first step in developing an alarm system against GICs is to forecast them. This is a challenging task, though, given the highly non-linear dependencies of the response of the magnetosphere to the SW. In the last few years, modern machine-learning (ML) models have shown to be appropriate and very good at predicting magnetic activity indices as the SYM-H. However, such complex models are on the one hand difficult to tune, and on the other hand they are known to induce potentially large prediction uncertainties which are generally difficult to estimate. In this work we aim at predicting the SYM-H index characterising geomagnetic storms one hour in advance, using public interplanetary magnetic field data from the L1 Lagrange point and SYM-H. We implement a type of ML model called long short-term memory (LSTM) networks. Our scope is to estimate -for the first time up to our knowledge- the prediction uncertainties coming from a deep-learning model in the context of SW. The resulting uncertainties turn out to be sizeable at the critical stages of the solar storms. Our methodology also includes an efficient optimisation of important hyper-parameters of the LSTM and robustness tests. This model represents the starting point towards our ultimate goal of providing a real-time prediction model of the GICs from extreme geomagnetic storms on the Spanish critical infrastructures.

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JA01d - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Research on modeling and predicting of GNSS satellite clock bias using the LSTM neural network model

DOI: 10.57757/IUGG23-3724 - LINK

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In the Global Navigation Satellite System (GNSS), the satellite clock bias (SCB) is one of the sources of ranging error, and the prediction capability directly affects the users navigation and positioning accuracy. The establishment of a reliable SCB predicting model is important for real-time precise point positioning, precise orbit determination and optimization of navigation message parameters. In this report, we apply a Long Short-Term Memory (LSTM) model for predicting BDS-3 SCB, which uses a multiple single-step predicting method to avoid error accumulation in the process. Short- (0 to 6 hours), medium- (6 hours to 3 days) and long-term (3 days to 7 days) predicting is performed, and the results are compared with those of two traditional models to verify the reliability and accuracy of the LSTM method. In the long-term prediction of BDS-3 SCB, LSTM improves the accuracy about 70% and 60% compared to the autoregressive integrated moving average (ARIMA) and quadratic polynomial (QP) model, respectively. This report also presents the results of predicting GPS and Galileo SCB using the LSTM method.

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JA01d - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Sporadic micro-meteoroid source radiant distribution inferred from the Arecibo 430 MHz radar observations with machine learning

DOI: 10.57757/IUGG23-2811 - [LINK]

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We present and discuss the outcomes of an investigation into the sporadic meteor radiant distribution using the High-Power Large Aperture Arecibo 430 MHz Incoherent Scatter Radar (ISR) located in Puerto Rico. There has been substantial meteor research using the Arecibo ISR, however, the sporadic meteor radiant distribution has remained elusive due to the radar's inability to estimate the vector velocity. In this work, a machine learning algorithm was specifically developed to determine the radiant density and speed distributions of the sporadic meteoroids observed at Arecibo. This algorithm incorporates a wide range of techniques, including stochastic gradient descent, and draws upon numerical modeling results and observational data to produce its results. The algorithm was trained using over 250,000 meteor observations carried out by the Arecibo radar between the years 2009 and 2017. Our results show that five of the six recognized sporadic meteor sources can be clearly identified, but no clear identification of the South Apex source emerged in the results. Instead, there is a broad distribution centered around the North Apex direction, with the peak density between +/-30° ecliptic latitude. Our analysis reveals that the Arecibo radar is most sensitive to meteors with an arrival angle between 30° and 60° but the radar cannot probe meteors that are moving straight into or perpendicular to the boresight of the antenna's radar. We show that 75% of the meteoroids sensed with the Arecibo radar usually travel in prograde orbits while most of the retrograde meteoroids typically move in inclined, low-eccentricity orbits.

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JA01d - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Forecasting solar wind speed from solar EUV images

DOI: 10.57757/IUGG23-2070 - LINK

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One of the main sources of solar wind disturbances are coronal holes which can be identified in extreme ultra-violet (EUV) images of the Sun. Previous research has shown the connection between coronal holes and an increase of the solar wind speed at Earth. In this study, we propose a new machine learning model predicting the solar wind speed originating from coronal holes. We detect coronal holes by applying a recently introduced segmentation algorithm to solar EUV images. Based on that, we derive time series of coronal hole characteristics, which are used as input to the model to predict the solar wind speed. Since coronal holes are structures that change over time, we also process their temporal evolution. We put a special focus on learning the geoeffective coronal hole areas, by splitting up the solar surface into multiple sectors of different latitudes and longitudes. This approach enables to predict the disturbances up to approximately 5 days in advance. We show that our model can accurately predict the solar wind speed with a temporal resolution of one hour during time periods when the solar wind is dominated by coronal hole activity. Moreover, we apply it to 10 years of data and compare our results to other state-of-the-art models.

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JA01d - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Plasma-sheet bubble identification using multivariate time series classification

DOI: 10.57757/IUGG23-1050 - LINK

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Plasma-sheet bubbles play a major role in the earthward transport of magnetotail particles. The most remarkable feature of bubbles is their fast bulk flow velocities, along with reduced plasma density and pressure accompanied by magnetic field dipolarization. These bubbles can be identified based on in-situ observations, but subjective ambiguity necessitates human verification, due to confusion with other phenomena mostly associated with magnetic reconnection and plasma waves. In this study, we aim to employ machine learning techniques to detect bubbles automatically and without prior subject expertise. To identify bubbles, we combine three distinct techniques: MINImally RandOm Convolutional KErnel Transform (MINIROCKET), 1D convolution neural network (CNN), and Residual Network (ResNet). The imbalanced training dataset consists of bubble and non-bubble events with a ratio of 1:40 from 2007 to 2020. The results indicate that the accuracy of the all three models is approximately 99%, and their precision, recall, and score are all above 80% for both the validation and test datasets. The three methods are combined with the intersection set as the minimum set of predictions and the union set as the maximum set. The union set can accurately identify 66.7% of plasma bubbles. The methods simultaneously reduce the number of false positives significantly. In the prediction of bubbles in observations made in year 2021 using union set, the bubbles obtained by the model are comparable to those discovered using traditional criteria and manual inspections.

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JA01e - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Application of convolutional neural networks for discriminating mining blasts and earthquakes

DOI: 10.57757/IUGG23-3221 - LINK

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University of Antananarivo Department of Physics, Antananarivo, Madagascar

Earthquake source is among the key element within the framework of seismic hazard. However, Seismic waves can be of natural origin or from anthropogenic sources such as mining-related events. Hence, without a proper approach for source discrimination, an earthquake catalog for hazard assessment can be contaminated. In this study, we propose a Convolutional Neural Network based on spectrograms to perform the waveform classification. It is targeted to applications in Madagascar.
The approach consists of three main steps: (1) generation of the time–frequency representation of ground-motion recordings (spectrogram); (2) training and validation of the model using spectrograms of ground shaking; (3) testing and prediction. To measure the compatibility between output predictions and given ground truth labels, we adopt the commonly used loss function and accuracy measure. Given that the spatial distribution of the seismic data in Madagascar is non-uniform, we perform two-step analyses. First, we adopt a supervised approach for 6051 known events in the central part of Madagascar. Then, we use the outcome for the second step training and perform the prediction for non-categorized events throughout the country.
The results show that our model has the potential to separate earthquakes from mining-related events. For the supervised approach, among the 20% used for testing, 97.48% and 2.52% of the events give correct and incorrect labels, respectively. These pre-trained data are subsequently used to perform predictions for unlabeled events throughout Madagascar. Our results show that the model could learn the features of the classes even for data coming from different parts of Madagascar.

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JA01e - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Extended range probabilistic forecasts of water temperatures at rivers and lakes in Switzerland using Machine Learning

DOI: 10.57757/IUGG23-1791 - LINK

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The increased frequency of the occurrence of drought in combination with heat waves in the recent years raises the need for forecasts of water temperatures to take timely measures to limit damages to aquatic ecosystems and mitigate losses. Furthermore, forecasts could allow identifying possible limitation of water use for cooling purposes by industry when water temperature are too high. Nonetheless, the usage of hydro-meteorological extended range forecasts with lead-times of several weeks is limited by now. Statistical models based on Machine Learning (ML) methods, have gained importance in recent years and show very promising results. However, there are several drawbacks of ML methods, like the lack of interpretability and the incorporation of uncertainty. We tested different ML methods at 60 stations, ranging from high alpine with glacier dominance to lowland, representing the diversity of Swiss runoff regimes. The aim is to analyse these methods in more detail with respect to the importance of the hydro-meteorological input variables used, the necessity of pre- and post-processing steps and the estimation of predictive uncertainties. A recently developed ML method for probabilistic forecasts, called Temporal Fusion Transformer, shows the best results and allows a detailed interpretation of the model results. The results for the period 2012 to 2022 highlight the importance of considering temporal and spatial aggregation of input data (e.g. applying wavelet transformations) as a pre-processing step and using post-processing methods, such as Nonhomogeneous Gaussian Regression, to improve the skill of the probabilistic forecast system.

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JA01e - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Generic seismic mass-movement detection leveraging unsupervised statistical learning methods

DOI: 10.57757/IUGG23-0742 - LINK

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[2]Swiss Data Science Center, sdsc, Zurich, Switzerland

With global warming potentially increasing the severity and frequency of hazardous mass-movements, monitoring such hazards is crucial to the population and critical infrastructure – especially in alpine areas. Monitoring and early-warning systems have the potential to improve the resilience of mountain communities to catastrophic events. Increasing the spatial coverage of seismic monitoring networks enables new warning perspectives if efficient algorithms screening the seismic data streams for hazardous mass-movements in real-time are available.

We propose to combine physical and statistical features of seismic ground velocity recordings from ground motion sensors such as seismometers. These features are then fed to an unsupervised workflow for mass movement detection. We evaluate the performance, consistency, and generalizability of unsupervised learning approaches by comparing a large number of fitted models obtained from various unsupervised methodologies. Focusing on debris-flow records at the Illgraben torrent in Switzerland, we present a mass-movement detector with high accuracy and early-warning capability that combines multiple statistical learning models into an ensemble classifier. Furthermore, our goal is to generalize this detector to measurements from other sites and thus to maximize its transferability.

Since our results aim to enable mass-movement monitoring and early-warning worldwide, Open Research Data principles like Findability, Accessibility, Interoperability and Reusability (FAIR) are of high importance for this project. We discuss how using the Renku platform (renkulab.io) of the Swiss Data Science Center ensures FAIR data science principles in our investigation. This is a key step towards our goal to enable seismology-based early warning of mass-movements wherever it may be required.

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JA01e - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Application of a neural network operator to fill long-term gaps of coastal sea-level data

DOI: 10.57757/IUGG23-1402 - LINK

Eun-Joo Lee[1], *Jae-Hun Park*[1]
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Sporadic misses in the tide gauge records occur frequently for a number of reasons, which hinders understanding of ocean physics in coastal regions. In other words, general-purpose time-series analysis and prediction methods require continuity of the data. To fill the sea-level data gaps, scientists have been working hard, but the existing reconstruction techniques have a disadvantage when missed sea-level records are longer than the timescales of coastal processes. To solve this problem, artificial neural network model is also being used to fill the gaps, but this method has a chronic problem that the shape of the target is fixed. To overcome this obstacle, we designed a model, named one-step prediction operator, which predicts the sea level after a unit of time. A data assimilation technique is additionally applied to merge seamlessly the model-predicted sea level with observed one. The recursivity of this model makes it possible to reconstruct missing data even longer than 72 hours successfully. The reconstructability of sea level records at 16 tide gauge stations around the Korean peninsula confirms that it can successfully reconstruct missing values with root-mean-squared errors of 0.5–1.3 cm on average.

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JA02a - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Satellite data intercalibration by means of data assimilation, an attempt on LEO satellites

DOI: 10.57757/IUGG23-2636 - LINK

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Understanding the dynamics of energetic electrons in the radiation belts is key to protect space borne equipment and astronauts on-board spacecraft missions. Therefore, global reconstruction of the near-Earth radiation environment should be available at all times and locations. Low Earth Orbit (LEO) satellites provide large data sets of the radiation belt region over a wide range of magnetic local times. However, the use of these data is complicated due to contamination of electron fluxes by protons and precipitating particles, leading to high variability of electron measurements, considerable instrumental errors and the need for background correction. In this study, we present a new intercalibration method for satellite measurements of energetic electrons in the radiation belts using data assimilation. We intercalibrate electron flux measurements of POES satellites against RBSP observations. For this, we use a reanalysis of the radiation belt region, obtained by assimilating RBSP and GOES electron data into 3-D Versatile Electron Radiation Belt (VERB-3D) code simulations via a standard Kalman filter. Since the reanalysis provides global reconstruction of the system, we can compare the POES data with our reanalysis and estimate the flux ratios at each time, location and energy. These ratios are averaged over time and space to obtain energy dependent recalibration coefficients. To validate our results, we perform a traditional conjunction study between POES and Van Allen probes. The conjunction coefficients and the DA estimated coefficients show very good agreement. The use of a data assimilative reanalysis significantly improves statistics and less data is necessary for the intercalibration.

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JA02a - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Interpretable machine learning procedure unravels hidden interplanetary drivers of the low latitude dayside magnetopause

DOI: 10.57757/IUGG23-4270 - LINK

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Interplanetary parameters, such as solar wind and interplanetary magnetic fields (IMF), drive the shape and size of the magnetopause jointly, which has complex relationships. In this study, we proposed an interpretable machine learning procedure to disentangle the influences of interplanetary parameters on the magnetopause standoff distance (MSD) and sort their importance in the MSD simulation. The magnetopause crossings of the THEMIS mission and interplanetary parameters of OMNI during the period of 2007-2016 are utilized to construct machine learning magnetopause models. SHapley Additive exPlanations (SHAP) is the foundation for an interpretable procedure, which introduces interpretability and makes the machine learning magnetopause model to be a “white box”. The solar wind dynamic pressure and IMF B_Z are widely considered the top two important parameters driving the MSD. However, the interpretable procedure suggests that the IMF magnitude (i.e. strength of the IMF) leads B_Z as the second most important interplanetary driver. This ranking result is unexpected, and it implies that the role of IMF magnitude is underestimated although magnetic pressure, which is a function of the IMF magnitude was considered in previous studies. The examination of disentangled effects of interplanetary parameters reveals that the combined influence of the IMF magnitude and B_Z can cause an MSD sag near B_Z = 5 nT. This is for the first time we conduct the interpretable concept into the machine learning model in the study of the magnetosphere.

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JA02a - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Picturing the global magnetosphere during storms and substorms by data-mining decades of spacecraft magnetometer observations

DOI: 10.57757/IUGG23-3583 - LINK

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The magnetosphere undergoes global dynamical reconfigurations termed storms and substorms in response to solar wind driving. Understanding how the 3D magnetic field and associated current systems evolve in time during these events is critical to characterizing the magnetosphere system. However, modeling storms and substorms using first-principles approaches is complicated because non-ideal magnetohydrodynamical processes, such as the formation of the storm-time ring current, thin current sheets, and magnetic reconnection, are key to their description. As such, several unanswered questions persist regarding the global morphology of these events and on their driving mechanisms. Here, we address these questions by empirically reconstructing the global 3D magnetic field and electric currents from decades of spacecraft magnetometer observations. For a given time of interest, the archive of observations is mined to form a subset of data from other times when the magnetosphere was in a similar storm and/or substorm state. This subset of data is used to fit an empirical model of the magnetic field that analytically describes the key magnetospheric current systems. This process is then repeated for each snapshot during an event, allowing for a quantitative dynamical picture to be reconstructed from the magnetometer data. We demonstrate that this data-mining based empirical approach reconstructs the primary features of substorms, including the thinning and stretching of the magnetotail followed by its rapid dipolarization, as well as the build-up of the storm-time ring current and pressure. This approach also locates the site of magnetotail reconnection during these events as confirmed by comparison with in-situ observations.

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JA02a - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Data assimilation into a machine learning-based emulator of global MHD simulation for analysis of the polar ionosphere

DOI: 10.57757/IUGG23-0339 - LINK

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The electric field in the polar ionosphere is imposed as a result of physical processes in the magnetosphere. The modeling of the magnetospheric processes is thus essential to reproduce physical phenomena in the polar ionosphere. Nowadays, magneto-hydrodynamic (MHD) models of the magnetosphere produce a realistic ionospheric potential pattern. Therefore, data assimilation into an MHD model would be a promising approach to reproduce ionospheric phenomena with high accuracy. However, the realistic MHD model is too computationally expensive to apply data assimilation. To overcome the problem of the computational cost, we employ a machine learning-based emulator of the global MHD model. The emulator is based on an echo state network model and efficiently mimics the MHD model to reproduce an ionospheric potential pattern under a give solar wind condition. As a pilot study, we assimilate the SuperDARN data into this emulator and obtain the global potential map. We will demonstrate the electric potential maps as a result of data assimilation into the emulator.

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JA02a - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Estimation of the topside ionosphere and plasmasphere by Ensemble Kalman Filter

DOI: 10.57757/IUGG23-2880 - LINK

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Up to 50% of the signal delays of L-band signals used in the Global Navigation Satellite System comes from the topside ionosphere and plasmasphere. In this study, we apply an Ensemble Kalman Filter (EnKF) approach to estimate the 4D electron density of the topside ionosphere and plasmasphere based on space-based STEC data. NeQuick model is used as background. The STEC measurements of eleven LEO satellites are used for the reconstructions. The majority of the approaches, working with EnKF, uses physics-based models for the propagation step. In our work, we investigate the question how the propagation step can be realized, in the case that a physical propagation model is not available or discarded due to computational burden. We explore different propagation models and compare them with the iterative reconstruction technique SMART+ for two periods of the year 2015 covering quiet to perturbed ionospheric conditions. We check the capability of the estimations to reproduce assimilated STEC as well as to reconstruct independent STEC measurements. The comparison with the assimilated STEC shows that during both periods all methods reduce the statistics (Median, SD, RMS) of the STEC residuals in comparison to the background model by up to 86%. In summary, the results indicate that the methods EnKF with exponential decay as propagation model (EnKFexp) and SMART+ perform best, reducing the independent STEC residuals by up to 64%, compared to the NeQuick model.

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JA02b - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Big data assimilation revolutionizing numerical weather prediction using Fugaku

DOI: 10.57757/IUGG23-1285 - LINK

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At RIKEN, we have been exploring a fusion of big data and big computation in numerical weather prediction (NWP), and now with AI and machine learning (ML). Our group in RIKEN has been pushing the limits of NWP through two orders of magnitude bigger computations using the previous Japan’s flagship “K computer”. The efforts include 100-m mesh, 30-second update “Big Data Assimilation” (BDA) fully exploiting the big data from a novel Phased Array Weather Radar. With the new Fugaku, we achieved a real-time BDA application to predict sudden downpours up to 30 minutes in advance during Tokyo Olympics and Paralympics. Moreover, Fugaku is designed to be efficient for both double-precision big simulations and reduced-precision ML applications, aiming to play a pivotal role in creating super-smart “Society 5.0.” We have been exploring ideas for improving the predicting capabilities by fusing BDA and AI. The data produced by NWP models become bigger and moving the data to other computers for ML or even simply saving them may not be feasible. A next-generation computer like Fugaku may bring a breakthrough toward creating a new methodology of fusing data-driven (inductive) and process-driven (deductive) approaches in meteorology. This presentation will introduce the most recent results from BDA experiments, followed by perspectives toward DA-AI fusion and expanding new applications beyond meteorology.

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JA02b - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Assimilation of near bound variables

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The largest errors in weather and climate predictions are generally associated with near bound variables such as aerosols, clouds and precipitation. These variables are "near-bound" in the sense that they are non-negative (bounded at zero) and that the error standard deviation of their observations and forecasts is not that different from the distance of their true value from the bound. Typically, the observation error standard deviation decreases as the true value of the variable approaches the bound and is typically specified by a relative standard deviation rather than an absolute standard deviation. The associated uncertainty distributions for both forecasts and observations of these variables are typically highly skewed and non-Gaussian. Sometimes the observed variables are non-linear functions of the underlying model variables. In this paper, we will show how well-known data assimilation frameworks such as Serial Ensemble Kalman Filters that assimilate observations in batches, Ensemble Kalman Filters that assimilate observations all at the same time (e.g. ETKF), and variational schemes such as 3DVar and 4DVar, can all be adjusted to greatly improve their ability to accommodate these bounded variables. The new theory will be explained and illustrated with simple examples in which the new method profoundly outperforms methods that attempt to treat these variables in the same way as other (Gaussian) variables.

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JA02b - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

A copula-supported Bayesian framework for spatial downscaling of GRACE-derived terrestrial water storage flux

DOI: 10.57757/IUGG23-3985 - LINK

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[1]*Insitute of Geodesy, University of Stuttgart, Stuttgart, Germany*
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[3]*INRAE, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Bordeaux, France*
[4]*Institut de Recherche pour le Developpement IRD, Laboratory of Space Geophysical and Oceanographic Studies, Toulouse, France*

The GRACE and GRACE-FO satellite missions provide mass variations as a fundamentally new observation type for a broad spectrum of novel applications in Earth science, including oceanography, geophysics, hydrology, and hydrometeorology. Despite all the key findings in hydrology, the utility of GRACE-derived Terrestrial Water Storage Anomaly and its time derivative Terrestrial Water Storage Flux (TWSF) have mainly been limited to large catchments due to their coarse spatial resolution. Here, we propose a method to downscale TWSF by incorporating available finer resolution data. We determine the downscaled TWSF and its uncertainty within a proposed Bayesian framework by incorporating the fine-scale data of TWSF and Soil Moisture Change (SMC) from different available sources. For the Bayesian ingredients, we rely on GRACE data to obtain the prior and rely on copula models to obtain nonparametric likelihood functions based on the statistical relationship between GRACE TWSF with fine-scale data. We apply our method to the Amazon Basin and assess the performances of our products from various fine-scale input datasets. Given the lack of large-scale ground truth for TWSF, we validate our results against space-based Surface Water Storage Change in the Amazon river system and also against the Vertical Crustal Displacements Change observed by the Global Positioning System. Overall, the results show that the proposed method is able to estimate a downscaled TWSF, which is informed by GRACE and fine-scale data. The proposed methodology can be extended to other coarse scale datasets, which are crucial for hydrological application at regional and local scales.

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JA02b - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Using FY-4A water vapor data to augment the NWP model forecasting performance over the South China

DOI: 10.57757/IUGG23-2169 - LINK

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Fengyun-4A (FY-4A) is the first satellite in the second generation of China's geostationary meteorological satellite series. The Advanced Geostationary Radiation Imager (AGRI) onboard FY-4A satellite can measure water vapor data at infrared band. In this study, to investigate the benefits of assimilating FY-4A water vapor data to weather forecasting performance over the South China region, we have performed the data assimilation experiments in the Weather Research and Forecasting (WRF) model for two periods with different water vapor conditions, i.e., February 2020 (dry period) and July 2020 (wet period). Two WRF schemes, i.e., WRF no data assimilation scheme (denoted as "WRF_NoDA") and WRF with assimilation of FY-4A Precipitable Water Vapor (PWV) scheme (denoted as "WRF+FY-4A"), have been implemented. The PWV and rainfall forecasting results of the two WRF schemes are validated by Global Navigation Satellite System (GNSS) PWV and the rainfall observations of the surface meteorological stations, respectively. The evaluation results show that, compared with WRF_NoDA scheme, WRF+FY-4A indicates a better performance in both PWV and rainfall forecasting. Specifically, with the assimilation of FY-4A PWV, the average root mean squares error of WRF PWV forecasting results for the first 12 h after data assimilation is reduced from 2.34 kg/m^2 to 2.25 kg/m^2 over the February period and from 4.39 kg/m^2 to 4.35 kg/m^2 over the July period. Additionally, after assimilating FY-4A PWV, the equitable threat score of accumulated rainfall for the first 12 h after data assimilation increases from 0.217 to 0.237 when using 10 mm/12 h as rainfall detection threshold.

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JA02b - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Localization and inflation in geomagnetic data assimilation: estimating the dynamic state of the Earth's outer core

DOI: 10.57757/IUGG23-0963 - LINK

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The core magnetic field of the Earth is generated by turbulent convection in the planet's electrically-conducting fluid outer core (geodynamo). While the outer core cannot be directly observed, measurements of the magnetic field at and above the Earth's surface provide clues to the state of the geodynamo (e.g., fluid flow and magnetic field in the unobserved deep interior).

In recent years, there has been growing interest in using data assimilation (DA) with 3-D numerical geodynamo models to better understand the Earth's outer core and forecast changes in the magnetic field. There remain however, significant challenges to overcome if such geomagnetic data assimilation (GDA) systems are to make optimal use of available models and data.

We present a set of numerical experiments with NASA's Geomagnetic Ensemble Modeling System (GEMS)—an ensemble Kalman filter (EnKF) based GDA system. The experiments focus on the development of "localization" and "inflation" techniques in GDA. While localization and inflation are common and often critical elements of DA systems in other applications (e.g. numerical weather prediction), localization has only recently begun to be systematically explored in GDA (Sanchez et al. 2019, 2020) and inflation has yet to be implemented. Determining an appropriate localization is difficult due to the spectral nature of the "data" being assimilated: low-degree spherical harmonics defining a magnetic potential near the core-mantle boundary. Our results show a significant improvement in forecasts of the magnetic field, particularly at smaller, less computationally demanding ensemble sizes.

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JA02c - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Whole atmosphere-ionosphere data assimilation and ensemble forecasting system

DOI: 10.57757/IUGG23-4819 - LINK

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[8]National Oceanic and Atmospheric Administration, Space Weather Prediction Center, Boulder, USA

Accurate forecasting of the ionosphere-thermosphere conditions is critical to radio communication, navigation, positioning, and satellite tracking. Located at the intersection between geospace and the Earth's atmosphere, the ionosphere-thermosphere is exposed to drivers from both space and terrestrial weather that operate over a wide range of spatial and temporal scales. With an increased availability of geospace data from recent missions such as NASA GOLD and NASA ICON as well as COSMIC-II, the use of a single seamless system, extending from the ground to geospace, to assimilate observations from both Earth and geospace observing systems is becoming a real possibility. This paper will report on recent progress with research efforts to develop a capability to assimilate geospace satellite data into a coupled whole atmosphere-ionosphere-plasmasphere model as an integral part of the NOAA National Weather Service's operational ensemble forecasting and data assimilation systems.

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JA02c - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Results on the assimilation of GOLD temperature and O/N2 Observations in WACCMX+DART

DOI: 10.57757/IUGG23-2957 - LINK

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The Global-scale Observations of Limb and Disk (GOLD) imager scans the Earth in the far ultraviolet wavelengths. Spectral measurements from GOLD are used to retrieve column integrated thermospheric neutral temperature (Tdisk) and oxygen to molecular nitrogen column density ratio (O/N_2) over about one fourth of the globe. The present investigation assesses the impact of GOLD disk temperatures and O/N_2 on the Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (WACCMX) using Data Assimilation Research Testbed (DART) ensemble Kalman filter. Observing System Simulation experiments (OSSEs), run with and without GOLD measurements, show that assimilating the two GOLD observations improves the root mean square error (RMSE) and bias of forecast and analysis states. Assimilation of actual GOLD Tdisk observations also shows improvement when compared to independent thermosphere and ionosphere measurements. Using a Specified Dynamics WACCMX (SD-WACCMX) run as the control simulation, we found that the RMSE improvements in the analysis effective temperature and O/N_2 are about 10.8% and 22.6%, respectively. Also, RMSE improvement in analysis electron column density is about 10% compared to the control simulation. Moreover, improvement in TEC RMSE is about 25% as observed from OSSE experiments that assimilated synthetic GOLD O/N_2 observations. These results demonstrate that assimilation of GOLD temperature and O/N_2 observations have a significant impact on the ionosphere-thermosphere model results.

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JA02c - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Monthly to seasonal statistical hydrological forecasts based on teleconnections

DOI: 10.57757/IUGG23-0502 - LINK

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The demand for accurate hydrological forecasts on longer time scales has been significantly increasing in many areas, e.g. waterway transport and flood protection. This, however, still presents a huge challenge using conventional dynamical models. As part of the project OptiVor of the Federal Institute of Hydrology (BfG), a new forecast method based purely on statistical relationships between meteorological/hydrological parameters and monthly river flow was developed and applied to German rivers. The main goal of this investigation was to find temporally stable, statistically significant connections on global and regional scales by learning from long historical data sets, with a time lag up to several months, in order to be able to use these in operational forecasting. Multiple linear regression was applied to create statistical models for each month and selected stations for lead times up to 8 months.

According to our investigation, global atmospheric teleconnections are of crucial importance regarding long-range hydrological predictions. Regional parameters, however, have a significant forecast value for the first 1 to 3 months. Preliminary results, also compared to conventional dynamical hydrological forecasts based on SEAS5 from ECMWF, are very promising and imply a potential basis for decision making. Further improvements are expected by combining statistical and dynamical methods, as well as applying machine learning tools in order to reveal even more valuable information from historical data sets. Another important point is the role of climate change that might have a large impact on existing meteorological and hydrological processes and thereby on the skill of data-driven methods.

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JA02c - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Spatialized data assimilation of snowdepth observations into a distributed model: Addressing the issues of equifinality and outlier observations

DOI: 10.57757/IUGG23-4944 - LINK

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In alpine regions, snow melt controls on freshwater availability, and the spatial variability of snow cover is large. Operational monitoring of snow water resources typically deploys snowpack models. However, snowpack models often struggle to capture the natural variability, because of shortcoming in either the meteorological forcing or the model itself. Data assimilation offers a way to bring models closer to reality, but reliable in-situ observations of the snowpack are not spatially exhaustive. In this situation, the performance of spatialized data assimilation typically suffers from two issues: equifinality between improved model results due to different adjustments, and a lack of robustness with respect to exceptional outliers in scarce observations.

In this work, we assess the potential of a Particle Filter (PF) to address both issues at the same time. To this end, we set up an ensemble of snowpack simulations [TJ1] with FSM accounting for meteorological and snowpack modelling uncertainties. The PF is applied to a dense network of snow depth stations covering entire Switzerland. Bi-weekly snow water equivalent and total density measurements are available on some of these (snow pit stations). We first assess the ability of our PF application to address equifinality by validating alternative simulations against independent multi-parameter observations. Then, we use a new inflation technique to mitigate the effect of outlier observations when propagating information across the whole network. This data assimilation framework is compared against an operational version of the snow model to assess its potential in a fully spatialized setting over the whole Switzerland.

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JA03a - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Digitising historical New Zealand paper magnetograms to extract one-minute data as input for modelling geomagnetic storms

DOI: 10.57757/IUGG23-0757 - LINK

Luke Easterbrook-Clarke[1], Stewart Hardie[2], Tanja Petersen[1], Ting Wang[3], Matthew Parry[3], Anna Davison[1], Pam Scowen[1], Craig J. Rodger[4], Tony Hurst[1], Esther Hiscock[5], Will Oliver[6], Clark Williams[7]
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[2]University of Canterbury, Electrical and Computer Engineering, Christchurch, New Zealand
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Extreme geomagnetic storms are likely to have catastrophic impacts to our modern increasingly technology-reliant society. Historical New Zealand magnetograms recorded on photographic paper from 1916 to 1991 (start of digital era) at the Amberley and Eyrewell geomagnetic observatories contain valuable information for statistical forecasting of extreme geomagnetic storms. To provide a digital long-term dataset as input for statistical models, the around 22,000 magnetograms that capture the continuous variations of the local Earth's magnetic field D, H and Z components have been scanned into images at high resolution and are now being converted into digital values at a 1-minute resolution.

We present our approach of using a combination of manual and automated digitisation techniques we have developed to translate the data from analogue traces into digital nanotesla values. The manual process that uses ArcGIS software as a tool focuses on the large geomagnetic storms with local k-index 7 and larger. We so far have captured 131 storm days from 1950-1990, with each storm taking up to 2 ½ hours of manual work. Software development (currently in MATLAB) for an automated "button-press" approach using image recognition techniques is targeting the lesser storms and quieter times. As part of quality control, the digitised values are cross-checked with published historical hourly mean values. The challenges we are encountering include hand-written notation, lack of labelling, gaps, offsets, overlapping and off-scale traces, varying line width and incomplete metadata.

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JA03a - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Geomagnetic observations at Clementinum/Prague Observatory (1839-1917) and the first magnetic survey in Central Europe

DOI: 10.57757/IUGG23-1784 - LINK

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[2]Earth Science Institute SAS, Geomagnetic Observatory, Hurbanovo, Slovakia
[3]Earth Science Institute SAS, Geophysical division, Bratislava, Slovakia

Shortly after Gauss's absolute method for measuring magnetic fields was invented (1832), and the bifilar device for observations of the geomagnetic field was constructed and put into operation in Göttingen (1837), geomagnetic observations also started at the Prague Clementinum observatory (1839). The beginnings of the observations at Clementinum were tightly connected with Karl Kreil, who become familiar with this new field of science at the Milan observatory. In Prague, he organized regular geomagnetic observations that even went on after his moving to Vienna (1851) to establish the Central Institute for Meteorology and Geomagnetism. The regular measurements in Prague persisted until 1917. The results were printed in yearbooks Magnetische und Meteorologische Beobachtungen zu Prag. The measurements were carried out manually. The declination was observed using the magnetic compass principle, while a bifilar apparatus was used to measure the horizontal intensity. Data from the period 1839-1871 were published in the divisions of the scale of the instrument. These data we analysed, transformed to physical units and made available to the users. In addition to regular daily observations, two categories of data with a higher cadence were provided in the first decade: (1) magnetic storms and (2) joint measurements organized in the frame of Göttingen Magnetic Union. In addition to the observatory practice at Clementinum, in the period 1843-1845, Kreil also carried out a magnetic survey in Bohemia, the first survey of this sort in the Central Europe. In the following years he continued the survey in other parts of the Austrian Empire.

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JA03a - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Extraction of historical magnetogram time series from French magnetic observatories

DOI: 10.57757/IUGG23-1615 - LINK

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A large collection of photographic paper magnetograms, covering globally an entire century is preserved in the archives of Chambon-la-forêt magnetic observatory, France. It contains magnetograms from various instruments and observatories: the National magnetic observatory (it moved from Parc-Saint-Maur, to Val-Joyeux, to Chambon-la-forêt), Bangui (Central African Republic), M'bour (Senegal), Pamatai (French Polynesia), and other observatories in metropolitan France at the beginning of the 20th century. Only values from tables of hand-written hourly values from the National magnetic observatory and overseas observatories had been digitised and made available to the scientific community.

In order to access additional information on the magnetic variations recorded on the magnetograms, we developed a recovering software: RECOV. It is based on MATLAB and can be run either as a MATLAB App, or as a standalone desktop application, with MATLAB Runtime. It provides an interface for manual selection of magnetic traces that are converted into magnetic variations and calibrated time series, if definitive hourly time series are available. The user can recover magnetograms of different quality, even cases when the magnetic traces cross the temporal axis, or wrap-around traces appear during the strongest storms. We aim obtaining recovered time-series with sampling every minute, with a reliability depending on the size and resolution of magnetic traces. We present results of recovered magnetic variations during magnetic storms of 1958 and comparisons between different instruments.

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JA03a - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Digitizing the Carrington 1859 storm: Magnetogram records from Greenwich and Kew observatories

DOI: 10.57757/IUGG23-1779 - LINK

Ciaran Beggan[1], Ewelina Florczak[1], Eliot Eaton[1], Ellen Clarke[1], Keitaro Matsumoto[2], Hisashi Hayakawa[2,3]
[1]British Geological Survey, Geomagnetism, Edinburgh, United Kingdom
[2]Nagoya University, Institute for Space-Earth Environmental Research, Nagoya, Japan
[3]RAL Space, Space Weather, Oxford, United Kingdom

Dedicated scientific measurements of the strength and direction of the Earth's magnetic field began at Greenwich and Kew observatories in London, UK, in the middle of the 19th century. Using advanced techniques for the time, light-sensitive photographic paper and light-levered reflections from magnetized needles, allowed continuous analogue magnetograms to be recorded. By good fortune, both observatories (which were located around 20 km apart) were in full operation around the so-called Carrington storm in the early September 1859 and the precursor storm in late August, providing as complete a record as possible. Based on digital images of the magnetograms and information from the observatory yearbooks and subsequent scientific papers, we extract and scale the measurements to SI units, allowing us to extract minute cadence values. The magnetogram records have several missing periods, lost as the traces moved off-page due to the magnitude of the storm. We present the most complete digitized magnetic records to date of the ten-day period from 25th August to 5th September 1859 encompassing the Carrington storm and its lesser recognized precursor which may have been just as large. We discuss some of the issues encountered in deciphering the old records and methods for cross checking and validating the output values.

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JA03a - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Core field and storm time geomagnetic dynamics enclosed in 1964-1970 satellite measurements

DOI: 10.57757/IUGG23-2043 - [LINK]

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In 2019, the World Data Center for Solar-Terrestrial Physics in Moscow digitized the archive of observations of the Earth's magnetic field carried out by the Soviet satellites Kosmos-49 (1964) and Kosmos-321 (1970). As a result, the scientific community for the first time obtained access to a unique digital data set, which was registered at the very beginning of the scientific space era. Herein, we first assess the quality of the obtained measurements by their comparison with the IGRF model. Second, we evaluate the historical models, which at that time were derived from the data of these two satellites. Third, we propose a new, improved model of the geomagnetic field secular variation based on the scalar measurements of the Kosmos-49 and Kosmos-321 satellites.
Space borne geomagnetic recordings of 1970 captured a strong magnetic storm on March 6-10, 1970. In addition to the data from the Kosmos-321 satellite, we also analyze geomagnetic data from the OGO-6 satellite, which was operational at the same time. We analyze time variations of external magnetic fields using satellite and ground-based observations. In particular, we identify the signatures of the storm-time ring current, equatorial and auroral electrojects.

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JA03b - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Digitization project of historical analogue magnetograms in Japan

DOI: 10.57757/IUGG23-1369 - [LINK]

Norimichi Mashiko[1], Shingo Nagamachi[1], Kenji Morinaga[1],
Takayuki Yamazaki[1], Seiki Asari[1], Junpei Oogi[1], Tohru Araki[2], Masahito Nose[3]
[1]Japan Meteorological Agency, Kakioka Mgnetic Observatory, Ishioka, Japan
[2]Kyoto University, Department of Geophysics- Graduate School of Science, Kyoto, Japan
[3]Nagoya University, Institute for Space-Earth Environmental Research, Nagoya, Japan

The Japan Meteorological Agency has been conducting long-term magnetic observations at Kakioka (1913-), Memambetsu (1952-) and Kanoya (1958-), and archived the observations in magnetograms. We have already converted these magnetograms into digital images at 600 dpi for the periods 1924-1983 (Kakioka), 1963-1984 (Memambetsu) and 1964-1984 (Kanoya). In 1956, time marks in the magnetograms were changed from 'gap' to 'vertical lines'. For the period after 1956, we have been producing 1-minute and 7.5-second digital values by our self-developed automated tracing software. The digitization was finished for the periods 1956-1983 (Kakioka) and 1968-1984 (Memambetsu and Kanoya), except for times of some abrupt phenomena. As automatic reading by the software is not applicable to such time intervals, we keep working on them with manual reading software.

Our ultimate goal is to complete digitization of all records prior to 1956, which involve a number of extreme events (PC, SFE, SC) including the 24 March 1940 event, the greatest SC event since 1868. 7.5-second data would be very useful resources for elucidating the Sun-Earth coupling processes. However, sharp peaks associated with SCs may not be adequately resolved even with those data. Additional information is desirably obtained by spotting apexes of individual peaks. Challenges to be addressed include: (1) difficulty in strict time identification due to the time mark gap, (2) difficulty in tracing lines due to dimness of the magnetograms, and (3) inaccuracy of the time axis due to paper distortion. New working tools and a certain amount of labor will be further required.

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JA03b - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Auroras and other celestial phenomena in medieval Arabic sources: A database

DOI: 10.57757/IUGG23-2820 - LINK

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Medieval Arabic historical writings commonly included reports of natural phenomena occurring on the Earth, in the atmosphere, or in the sky. Since the methods for recording these phenomena were not developed scientifically, different authors were engaged differently with the details of these phenomena in their records. Yet, such records are valuable sources of knowledge for historians studying these natural phenomena in their historical contexts. A few studies on such records have been published, each of which focuses on one or several kinds of phenomena. Nevertheless, no systematic effort has been made to analyze the precision of these records, their methodology, and their possible reliance on earlier sources. In this project, we aim to present these records in the form of a digital platform that will allow scholars to study and investigate their accuracy. Special attention is paid to the literary aspects of these historical records.

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JA03b - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Toward a new revised collection of sunspot group numbers with emphasis on 17th and 18th century observations

DOI: 10.57757/IUGG23-3344 - LINK

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[2]*Nagoya University, Institute for Space-Earth Environmental Research, Nagoya, Japan*

In this work, we present the collective effort since 2016 to improve our knowledge of the solar activity of the last four centuries based on the daily counts of the number of sunspot groups. Multiple authors have shown that the main task that can improve our knowledge of the solar activity of the last four centuries is the revision and recovery of old telescopic observations of sunspots, especially in the 17th and 18th centuries where there are the largest gaps and the most important uncertainties. We place special emphases on the observations made during the Maunder Minimum (1745-1715), a time with a very low solar activity.

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The ISIS Topside Sounder Project - Rescuing a Unique Ionospheric Data Set

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Modeling of the topside ionosphere (from F peak to ~2000 km) suffers from a scarcity of data because ground ionosondes only reach up to the F peak. Millions of topside ionograms had been recorded by the Alouette 1,2 and ISIS 1,2 satellites between 1962 and 1990 that were never fully analyzed. The satellites carried topside sounders, the satellite equivalent of the ground-based ionosonde, and provided the first global view of the topside ionosphere. The topside sounders were designed as analog systems that recorded ionograms on 35 mm film for analysis by visual inspection. Many nations participated in the data analysis process that involved manual scaling of the ionograms and inversion into electron density profiles. But because of the tedious manual process only a small percentage of the recorded ionograms was converted to electron density profiles. We were able to digitize a significant portion of the 60 satellite years of analog data before the tapes were discarded. In a second step we worked with a team at the University of Massachusetts Lowell who developed the Topside Ionogram Scalar with True-Height inversion (TOPIST) software for the automated scaling and inversion of the traces on the digital ionograms into electron density profiles thus avoiding the very limiting manual process.

As a result of our project close to a million digital topside ionograms and electron density profiles are now available for browsing/plotting/downloading at NASA's Space Physics Data Facility (https://spdf.gsfc.nasa.gov). We will review some of the science results based on the digital data.

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JA03b - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

A review of early graphical continuous record and their technical problems

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Obtaining continuous record of Earth variables, now a standard, has been a problem for centuries. First attempts for graphical continuous records started in the XVIII Century; but those early attempts did not generalize. It was necessary to wait until the second half of the XIX Century for their generalization.

The continuous record was hampered by technical problems. Continuous analogue records were obtained on paper support (smoked, ink photographical, etc.) and a main issue was to get enough power for the mechanism moving the paper sheets. A second problem was to get a stable speed for the records. All these problems were not really overcome until the second half of the XX Century, when electrical power generalized all over the world and allowed powerful and precise mechanism to sustain properly the advancement of the recording sheets.

Other problems were the limited amplitude and resolution posed by the sheet's dimensions and the paper speed, as well as the frequency band wide required. These problems forced original and specific solutions for each case. In fact, graphical continuous recording was a continuous trade between the desired record and the technical available solutions,

This presentation reviews the evolution of the analogue continuous record in several fields of geophysics (meteorology, seismology, oceanography, geomagnetism) pointing some insights allowing a better interpretation of the recorded series.

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JA03b - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Preliminary study of tectonic tremor location using analog seismograms on recording paper of the Kanto-Tokai Observation Network

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Slow earthquakes have been extensively studied since the discovery of tectonic tremor (hereinafter, tremor; Obara, 2002, Science). However, the past activity of tremor before 2000 is still not clear in the Nankai region, Japan. National Research Institute for Earth Science and Disaster Resilience operated the Kanto-Tokai Observation Network since late 1970, and has stored analog seismograms on recording paper. This is a unique dataset to reveal tremor activity in the Tokai region in 1980's. In our previous study, we developed a tool to digitize data from scanned images of these seismograms (Matsuzawa and Takeda, 2021, AGU). However, it was difficult to locate tremor using the digitized data directly, due to the contamination of time marks for each second. We report a preliminary result of tremor location using these seismograms, reducing the effect of time marks.
At first, we modeled the time series of time marks as repeating spike-like signals at the interval of 1 s. The modeled time series are subtracted from the original data to reduce the effect of time marks. By this correction, peaks at 1Hz and 2Hz are less dominant in the power spectrum. Then, we tried to locate tremor in the Tokai region at 5am on Apr. 27, 1988, using the corrected seismograms at four stations. We located tremor close to the Shimoyama station in the central Tokai region at 5:33-5:34am, based on the differences of arrival times which are estimated by the correlation of envelope waveforms.

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JA03c - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Sustainable preservation and digitization of analogue seismic records in Germany.

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The importance of preserving analog seismic data has been fully acknowledged in the seismological community for years. Now, the Federal Institute for Geosciences and Natural Resources (BGR), Germany, has announced a pilot study which aims to estimate the possibility of digitizing all seismic records in Germany. This study is performed by researchers from the Universities of Potsdam and Hamburg who have strong expertise in working with analogue seismic data.

There are at least 12 institutions in Germany which store more than one million analog seismic records and corresponding metadata. We have contacted the institutes representatives and have their support for the project. We plan to visit all archives to document their content in a comprehensive catalogue with detailed description of data and metadata.

In order to estimate the workload for scanning and digitizing all German archives and for quality control, a test run will be performed. This step includes the scanning and digitizing of a selection of paper seismograms into a digital time-series and scanning of paper bulletins and station books. The seismograms from three stations will be collected for a limited continuous time period. One or two events will be selected to determine earthquake source parameters (e.g., location, magnitude and focal mechanism). As a result, a guidebook with a feasible workflow, recommendations (e.g., for scanning facility, digitization software), and pitfalls (e.g., lacking proper scaling) will be prepared.

Finally, we will provide a long-term concept for preservation and digitization of all analogue seismic records and corresponding metadata available in Germany.

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JA03c - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Filling a ~60 years void of instrumental parametric data in observational seismology

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Before the introduction of online data sharing and computer-based archiving and processing of instrumental data, the results of observational analyses of seismograms were stored in printed bulletins produced by individual observatories and national as well as regional agencies around the world. Since late 2010, many digitization were undertaken by the International Seismological Centre (ISC, www.isc.ac.uk). With this contribution we aim to summarize the wealth of (new) data the ISC brings to the seismological community for earthquakes occurring as early as 1904. Therefore, the data digitized in these years fills a large gap in electronic bulletin data availability and complements the data freely available from the ISC Bulletin starting in 1964. We expect this data to be an asset for studies of earthquakes occurred in the pre-digital era as well as for seismogram digitization initiatives.

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JA03c - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Lessons from preserving and extracting historical seismic data

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Over the last 150 years, the seismological community has accumulated millions of ground motion records on both paper and film. While almost all analog seismic recording ended by the late 20th century, replaced by digital media, the still-extant archives of paper and film seismograms are invaluable for many ongoing scientific applications. This long-running record of ground motion is crucial for developing understanding of how both natural and anthropogenic events have changed the Earth and its processes throughout the last century. Legacy seismic archives are the sole source of data from the remarkably large earthquakes of the 1960s, above-ground and submarine nuclear tests, and over a century of hurricane-related signals that are changing with global climate.Today, most of these records are housed in institutions with limited resources, which must prioritize certain objects or types of objects for preservation and access. For example, when seismologists today are forced to triage collections, the bulky paper-records are oftentimes more at-risk for deaccessioning than more compact film copies. However, alterations introduced in reformatting (i.e., paper to film) as well as preservation requirements of the various records are not often fully understood or appreciated. To make these decisions in an informed way, it is vital to know the stability of the recording media and the level of accuracy that can be obtained from these different records. For example, image distortion and available color depth in paper and microfilm copies can result in discrepancies in derived time series which could lead to significant errors in products such as nuclear test yield and location.We present lessons learned from recent experiences with modern archiving and processing of legacy seismic data. These include techniques for data rescue (including both scanning and conversion to time series), the importance of characterizing the full processing chain, and the importance of involving archivists and citizen science in preservation efforts.

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Utilization of historical data in the Geosciences: The case of Extremadura region (Spain)

DOI: 10.57757/IUGG23-3359 - LINK

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Nieves Bravo-Paredes[1], *Víctor M.S. Carrasco*[1], *Lucía Díaz-Condiño*[1], *María Cruz Gallego*[1],
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[1]*Universidad de Extremadura, Departamento de Física, Badajoz, Spain*
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Departamento de Didáctica de las Ciencias Experimentales y Matemáticas, Cáceres, Spain

We review in this work the activities carried out by our geoscience research group using historical data especially focused on the Extremadura region (SW Spain). We describe some recent works such as the use of correspondence by the Duke of Feria to create precipitation and temperature indices for the period 1750-1840 or the systematic recovery of old meteorological data (including data on unusual variables related to solar radiation). We also describe the work we are doing recovering news about events of interest in geosciences from regional newspapers (meteorological phenomena, earthquakes, fireballs, aurorae at low latitude, ...). Finally, we show a rare episode of great thunderstorms that devastated the Extremadura region in June 1925.

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JA03c - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Recovering the Italian daily hydrological measurements with a citizen science approach

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The availability of long and reliable records of hydrological data is essential for hydrological analyses, especially under climate change.
In Italy the collection of hydrological data has been managed at the national level by the National Hydrological and Mareographic Service (SIMN) since early 1900. The dismantlement of the SIMN, that occurred about 30 years ago, resulted in data collection being transferred to the regional level. This change has determined problems in the availability of complete series for the whole country. Historical hydrological measurements are usually available only in the printed version of the Hydrological Yearbooks and limited efforts have been spent to digitize this collection. This lack of information is critical in a nation like Italy, with both a complex geomorphology and a changing climate.
Despite the remarkable improvements achieved in recent years by Optical Character Recognition software and machine learning / artificial intelligence techniques, in several cases the most accurate digitization approach is still based on manual transcription. Within the SIREN (Saving Italian hydRological mEasuremeNts) project we aim to digitize these data by crowd-sourcing the recovery of hydrological measurements from historical Hydrological Yearbooks to produce a consistent dataset. Phase 1 of the SIREN project will be devoted to recover more than 17000 annual tables of daily discharge measurements. This considerable amount of data not only will allow us to better understand the climate of the past century but will also serve to inform models whose objective is to estimate how the climate and the hydrological cycle will change in the future.

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Using citizen science to rescue sea level data in danger

DOI: 10.57757/IUGG23-0938 - LINK

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Long term records of observations of sea surface height from tide gauges form the backbone of our understanding of variability in mean sea level, tides and storm surges. Unfortunately, many longer records are still inaccessible, as the data only exist as paper records, or have been scanned but never digitised into usable data. Recovering historical observations and making them freely available makes a vital contribution to our ability to understand the past and forecast what might happen in the future.

In 2021, we coordinated about 4000 volunteers through the Zooniverse website to transcribe scans of handwritten ledgers containing 15-minute tide gauge records from 1853 to 1903 from two sites in North West England. We report on the feasibility of using this process for other rescue projects, the unusual quality control requirements for volunteer transcriptions, and present the newly restored data with 19th century tides, storm surges and sea level. The 1903 data have contributed to reanalysis of a severe storm event, together with newly digitised pressure records.

We will also discuss plans for distributing the recovered data in a FAIR way, and we will also present some of our ideas to rescue more data, particularly from tidal charts.

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JA04a - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Errors estimates for GNSS-Acoustic measurements of the Alaska subduction zone

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[5]University of California- San Diego, Scripps Institution of Oceanography, La Jolla, USA

We installed and made measurements on three ocean-bottom GNSS-Acoustic (GNSS-A) sites in 2017-21 spanning 3 sections of the Alaska subduction zone to determine the along-strike variability of megathrust coupling. Interpretation of the resulting time series requires the associated errors and their spatial and temporal correlation. The primary source of error for GNSS-A is change in the ocean sound speed field. Our observing strategy is designed to mitigate vertical changes in the sound speed profile, the impacts of lateral variations in sound speed, however, are only somewhat reduced through this observing geometry. Here we identify and estimate the magnitude of lateral sound speed variations on our GNSS-A measurements. The error structure reflects the contribution of many different oceanographic processes. For 10-60 min time periods perturbations from internal waves are the dominant feature. Longer period perturbations are generated by tidal currents, transient events such as eddies, and seasonal processes. We use an autocorrelation approach to examine the error structure within the GNSS-A residuals to estimate the period and magnitude of the internal waves during our observation campaigns. We use the Hycom high resolution numerical ocean model to explore the lateral variations of the sound speed field at longer spatial and temporal scales and provide a statistical characterization for the perturbations in centroid position estimates due to lateral gradients captured by the model. Combining these with predictions for the times of our observations full a-priori variance-covariance matrix can be created for modeling our position time-series.

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JA04a - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Advancement of accuracy and frequency of the GNSS-A seafloor crustal deformation observation

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Although GNSS-A (Global Navigation Satellite System–Acoustic ranging combination technique) observation is a technology that measures steady or sudden seafloor crustal deformations at the centimeter level, the technical capabilities are inferior to those of terrestrial GNSS observation in terms of accuracy and frequency. Therefore, many technological developments are currently underway.
We are conducting error factor analysis through simulation and experimental research in order to improve the observation accuracy and frequency of SGO-A, which is operated by the Japan Coast Guard. By investigating the effects of high-rate GNSS on GNSS-A, development of representation and modeling methods of underwater sound speed fields, and equipment and angle-dependent characteristics due to sonar characteristics, we are progressing in developing quantitative evaluation and correction methods for errors. The accuracy research of GNSS-A is closely related to the accuracy research of GNSS. In the near future, we would like to construct a unified error correction method for instruments and observation envirnments, similar to GNSS.
Regarding the observation frequency, we have reached the limit of observation frequency using ships around 2020, and the development of new sea surface platforms is necessary. For example, research on autonomous buoys (wave glider), moored buoys, and flying-boat type UAVs is underway. Various marine engineering applications other than GNSS-A are underway for a research field of sea surface platforms, and this field may be further updated in the future. In this presentation, we will also discuss new sea surface platforms for GNSS-A.

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example, research on autonomous buoys (wave glider), moored buoys, and flying-boat type UAVs is underway. Various marine engineering applications other than GNSS-A are underway for a research field of sea surface platforms, and this field may be further updated in the future. In this presentation, we will also discuss new sea surface platforms for GNSS-A.

JA04a - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Decadal postseismic deformation of the 2011 Tohoku-oki earthquake revealed by GNSS-acoustic observations using manned and unmanned sea surface platforms

DOI: 10.57757/IUGG23-0753 - LINK

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While 12 years have already passed since the 2011 Tohoku-oki earthquake (M9.0), postseismic deformation of the earthquake is still ongoing. In order to detect the postseismic deformation of the Tohoku-oki earthquake, we have been performing repeating observations at seafloor sites for the GNSS-Acoustic (GNSS-A) geodetic observation technique since 2012 using both manned research vessels and an unmanned surface vehicle, called Wave Glider (WG), as a sea surface platform. We developed and tested a system to conduct the GNSS-A observations using the WG in 2019 and have continuously operated the system twice a year since 2020, visiting many (around 15) observation sites. Based on the observation data collected using research vessels and the WG, we estimated the displacement time series of the seafloor transponder array of each site. The spatio-temporal variations in seafloor crustal deformation after the 2011 Tohoku-oki earthquake indicate that the viscoelastic relaxation is the primary cause of the westward motion around the main rupture area of the M9 event, while the afterslip on the shallow plate interface played an important role in producing eastward displacements in the region south to the main rupture area. With respect to the region north to the main rupture area, no distinct spatial deformation pattern has been observed. This implies that multiple factors, i.e., viscoelastic relaxation, afterslip, interplate locking, and episodic slow slip events, are responsible for the complicated spatial deformation in this region. We will also report the current conditions of the equipment for GNSS-A observations in the presentation.

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JA04a - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Another implementation of GARPOS-MCMC for the full-Bayes GNSS-A seafloor precise positioning analysis with the widely applicable Bayesian information criterion

DOI: 10.57757/IUGG23-1474 - LINK

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[2]University of Tokyo, Institute of Industrial Science, Tokyo, Japan

As one of the seafloor geodetic techniques, precise seafloor positioning by the GNSS—Acoustic ranging combination technique (GNSS-A) is applied for the observations of the crustal deformation in the plate subduction zones (e.g., Spiess et al., 1998; Fujita et al., 2006). For the precise positioning with the GNSS-A, it is required to appropriately cancel or correct the effects of sound speed variation on acoustic travel time. We have developed static GNSS-A analysis methods where the sound speed effects were simultaneously corrected with well-distributed acoustic data, by introducing the perturbation field model (Watanabe et al., 2020). Based on the empirical Bayes approach, it was implemented in an open-source software GARPOS (the latest version is v1.0.1, https://doi.org/10.5281/zenodo.6414642), in which hyperparameters are selected to minimize the Akaike Bayesian Information Criterion (ABIC; Akaike, 1980). Watanabe et al. (under review, preprint https://doi.org/10.21203/rs.3.rs-1881756/v1) developed the upgraded version of GARPOS, i.e., GARPOS-MCMC (the latest version is v1.0.0, https://doi.org/10.5281/zenodo.6825238), with a full-Bayes GNSS-A analysis scheme, where the hyperparameters are also expressed as probability density functions. The parameters are estimated with the Markov chain Monte Carlo method, which enabled us to directly sample from the joint posterior of parameters including any hyperparameters and evaluate the correlations between those parameters. However, it requires computational resources as the number of acoustic data becomes large. To overcome the disadvantage, we introduced the widely applicable Bayesian information criterion (WBIC; Watanabe, 2013) for model selection for some hyperparameters, to partly take an empirical Bayes approach, and implemented it on GARPOS-MCMC.

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JA04a - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Systematic error estimation and modeling for underwater acoustic positioning and augmented navigation

DOI: 10.57757/IUGG23-0705 - LINK

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Abstract: The performance of underwater acoustic positioning and navigation is greatly influenced by the systematic errors related to the time delays and the time-varying sound speed. Therefore, one of the key issues of underwater acoustic positioning and navigation is how to reduce the effect of the systematic errors. In this study, we propose a systematic error estimation and modeling method. The method firstly constructs an improved acoustic observation model based on the cubic B-spline curve and the nadir total delay (NTD), meanwhile, the transponder coordinates as well as the systematic errors related to the sound speed and the time delay are estimated. Then we use the polynomial fitting method to construct systematic error model and broadcast to underwater acoustic navigation user. Finally, the augmented underwater acoustic navigation is performed based on correction information. The proposed algorithm is verified by a real experiment for the underwater acoustic positioning and navigation in the South China Sea. The results demonstrate that the proposed algorithm can efficiently reduce the influence of systematic errors, thus improving the underwater acoustic positioning and navigation accuracy. The inside precision of seafloor datum positioning can reach cm level. The root mean square error (RMSE) of underwater acoustic navigation is about 1 m within the datum network compared to the results of global navigation satellite system (GNSS).

Keywords: Underwater acoustic positioning and navigation; Systematic error; Time delay; Sound speed error; Nadir total delay

Acknowledgments: The study is financially supported by Laoshan Laboratory (LSKJ202205104), National Key Research and Development Program of China (2020YFB0505804), National Natural Science Foundation of China(41931076), Foundation of Key Laboratory of Marine Environmental Survey Technology and Application, Ministry of Natural Resources, China (MESTA-2020-B013).

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JA04b - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Geophysical Exploration of Deep-Sea Massive Sulphide Deposits

DOI: 10.57757/IUGG23-3278 - LINK

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Deep-sea hydrothermal fields (HTF) associated with the formation of seafloor massive sulphides (SMS) may become a future source of high-tech metals, which are in high demand for the energy transition. The identification and evaluation of the deposits are challenging, as they are relatively small and form in complex terrain at mid-ocean ridges, island arcs, or back-arc spreading centres. Active HTFs are often accompanied by black smokers and have an abundant, environmentally sensitive fauna. Tt is generally agreed that they should be excluded from possible mining. The economically interesting inactive and extinct fields often miss the characteristic seafloor expressions and distinct vent fauna, and may be hidden under a thin layer of sediments. Thus, video observations and sampling are not sufficient to evaluate the extent of the SMS deposit.Since 2015, BGR undertakes annual research cruises to the German SMS license areas along the Indian ridges (INDEX project) with the aim to find prospective mineral deposits and establish environmental baseline studies. Several unknown HTFs have been identified using a multidisciplinary approach. An important aspect in mineral resource assessment is the inner structure and size of the deposits, which can be addressed by geophysical methods. In addition to magnetic and bathymetric surveys, we apply electromagnetic and self-potential methods on deep-sea sensor platforms. We can clearly relate electrical conductivity, magnetic and self-potential anomalies to previously identified sulphide sites of active and inactive hydrothermal areas. However, deriving spatial constraints is still one of the most challenging and vital disciplines of geophysical exploration in this context.

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JA04b - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Computation of the electrical conductivity for rocks containing smectite

DOI: 10.57757/IUGG23-1288 - LINK

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Electromagnetic surveys such as magnetotellurics are known to be sensitive to the presence of smectite, which is abundant in subduction zones. However, the contribution of smectite to bulk conductivity is complex and still needs to be quantitatively understood better. Therefore, in this study, we investigated the effect of smectite on bulk conductivity by numerical modeling using the finite element method. In our simulations, we investigated the effects of four conditions: porosity, fraction of smectite in the quartz matrix, temperature, and NaCl concentration of pore water. Here, we randomly assigned each element's conductivity tensor of either material: smectite, quartz, or pore water. In addition, we introduced an anisotropy to the conductivity tensor of smectite between the directions parallel and perpendicular to the T-O-T layer. Meanwhile, the conductivity tensors of quartz and pore fluid were considered isotropic. The simulation results showed that the spatial arrangement of the materials significantly affected the bulk conductivity for the porosity greater than 0.01. In contrast, for smaller porosity, the effect of the spatial arrangement was almost negligible, and the volume fraction of smectite, pore water salinity, and temperature controlled the bulk conductivity. These results suggest that proper parameterization of the element arrangement patterns is essential when calculating the bulk conductivity of smectite-bearing rocks.

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JA04b - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Accurate modelling of marine magnetotelluric data using high-order finite element methods

DOI: 10.57757/IUGG23-3461 - LINK

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Center for Geophysical forecasting- Department of Electronic systems, Trondheim, Norway

Magnetotelluric (MT) signal is a natural electromagnetic (EM) response that can penetrate up to hundreds of kilometers deep in the earth's interior. When deployed at the seafloor, ocean bottom MT receivers provide us quality EM data that can decipher both regional and large-scale conductivity structures underneath the seafloor. Knowledge of such structures is critical in the studies of Earth's interior and marine geohazards. A key step in interpreting these deep sea EM data is accurate modelling of the data over various plausible marine conductivity models, where the existence of highly conductive sea water poses as a main challenge in improving the modelling accuracy. The accuracy degeneration issue caused by the seawater becomes more severe for three-dimensional (3D) studies in which fine discretizations of seawater layer are often required. To ensure modelling accuracy, we have developed high-order finite element (FE) modelling techniques in conjunction with unstructured triangular (2D) and tetrahedral (3D) meshes. Using the high-order FE methods, excessively large meshes are avoided since the seawater layer does not need to be finely discretized. Our modelling code has been tested and can provide accurate modelling results of marine MT data for a large range of frequencies. The modelling accuracy is demonstrated using both 2D and 3D examples. Using the newly developed code, we aim to study deep conductivity structures over various seafloors of interest.

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JA04b - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Lithosphere-asthenosphere boundary dynamics revealed from magnetotelluric data at the Mid-Atlantic Ridge

DOI: 10.57757/IUGG23-4635 - LINK

Shunguo Wang[1], *Ståle Emil Johansen*[2]
[1]*NTNU, Department of Electric Systems, Trondheim, Norway*
[2]*NTNU, Department of Geosciences and Petroleum, Trondheim, Norway*

Lithosphere-asthenosphere boundary (LAB) is essential for tectonic plates as it is the base of the plates and enables movement of the plates. However, the nature of the LAB, including its depth, is still elusive. The definition of LAB varies from study to study by using different geophysical data. Oceanic LAB has a simpler history than continental LAB, therefore it is ideal to study the nature of LAB beneath the seafloor. Partial melt is one feature of LAB suggested in multiple geophysical and petrophysical studies. The magnetotelluric method is sensitive to partial melts and is one of the most effective methods to map partial melts and study LAB. Therefore, we have collected three different datasets in Northern Middle Atlantic Ridges to further study the electrical property of LAB. The eLAB at different latitudes is more dynamic than we previously thought. The resistivity model of LAB can be simple at one location and complicated at another location of the Mid-Atlantic Ridge. More interestingly, at some locations, the upwelling magma is not seen beneath the middle ocean ridge in the resistivity model, which is supposed to be the supplier of seafloor spreading materials. These findings enrich the understanding of the geodynamics of Earth and suggest that a more complicated model is necessary to represent LAB.

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JA04b - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Seafloor Slumping due to Gas Hydrate dissociation : A Case Study from Krishna-Godavari basin

DOI: 10.57757/IUGG23-3159 - LINK

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The Krishna Godavari (KG) basin is a passive margin basin with slumps, mass flows occurred due to rapid sedimentation, gas hydrates etc. To understand the dissociation mechanism of gas hydrates on slumping/sliding, 3D seismic data from a small region in the KG basin is examined in the present study. Seismic Interpretation of the data reveals shoaling of the Bottom simulating reflector (BSR) followed by truncation further downslope, creating slope failure. The role of pressure and temperature in altering the hydrate stability is studied and found that the temperature change is the main parameter that controls the gas hydrate stability. The Base of the hydrate stability zone (BHSZ) during the Glacial time and the present day is computed with varying Geothermal Gradients (GTG) of 45 ± 3° C/ km. The obtained results show that the BHSZ has shifted by 80 m post-glacial at a water depth of ~ 1000 m. Our results also shown that changing the GTG in the range of 43-48° C/ km has caused only a ten-meter change in the shift, but changing the seafloor temperature from 4-6.5°C has caused 80 meters shift in the BHSZ. We find a close correlation with the depth of dissociation inferred from interpretation of seismic data and dissociation temperature computed. Two slumping features were observed in the seismic data of varying size; the smaller one is attributable to the over pressurized zone below the BSR and the larger one (~21km), seems to have formed as a result of gas hydrate dissociation.

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JA04c - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Bathymetry changes from ICESAT-2 -A case story from Moreton Bay Australia

DOI: 10.57757/IUGG23-4660 - [LINK]

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[3]*University of Tasmania, Institute for Marine and Antarctic Studies IMAS, Hobart- Tasmania, Australia*

The bathymetry of coastal bay environments, like Moreton Bay around Brisbane in eastern Australia, is constantly reworked because of changes in the patterns of energy dispersal and related sediment transport pathways. Updated and accurate bathymetric models are a crucial component for scientific, environmental, and ship safety studies.

NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was launched in September 2018 and carries a single instrument, ATLAS (Advanced Topographic Laser Altimeter System). ATLAS is a green wavelength, photon-counting lidar, enabling global measurement and monitoring of elevation with a primary science focus on the cryosphere. However, ATLAS's green laser frequently penetrates the air–water interface, and under the right conditions and in shallow waters (<40 m), these photons are reflected back to ATLAS after interaction with the ocean bottom.

An Australian Research Council funded research project "Enhancing marine bathymetry using new-generation satellite sensors" commenced in 2022. We present the first results from this project on the use of ICESAT-2 along selected 91-day repeat tracks across Moreton Bay to investigate changes in bathymetry over the past 4 years. Moreton Bay has had significant changes in bathymetry with time, but significant suspended sediment creates problems for ICESat-2 photons to propagate through the water column.

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JA04c - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Monitoring seafloor deformation using bottom pressure and ocean models: An A-0-A experiment in the context of the Mayotte volcanic crisis

DOI: 10.57757/IUGG23-4991 - LINK

Yann-Treden Tranchant[1], Valerie Ballu[1], Denis Dausse[1], Laurent Testut[1]
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The use of ocean bottom pressure (OBP) records is crucial to monitor seafloor motion caused by tectonic and magmatic processes. However, accurately monitoring seafloor deformation through time with OBPs is challenging due to instrumental drift and oceanic variations at different timescales. In the context of the Mayotte volcanic crisis in the western Indian Ocean in 2018, three RBR Ambient-Zero-Ambient (A0A) drift-controlled pressure gauges were consecutively deployed (2020-2022) to monitor seafloor vertical deformation. The A0A system estimates instrumental drift by periodically venting ocean pressure to a reference atmospheric pressure.

Since no significant vertical ground displacements have been recorded by ground GNSS stations since 2020, this study aims to assess the calibration method of the A0A system, reduce oceanic “noise” in corrected OBP records, and discuss the ability to observe any seafloor deformation offshore Mayotte. Numerical models, including ocean circulation (OGCMs) and barotropic models, were used to understand the influence of the different processes and to reduce the oceanic “noise” in drift-corrected OBP records. Additionally, temperature and salinity data collected by repetitive glider transects were used to validate OGCMs in the region and quantify the contribution of unresolved processes to OBP records.

Our results provide valuable insights into the feasibility of using numerical modeling for improving the accuracy of OBP-based monitoring in the context of the Mayotte volcanic crisis as well as for other seafloor deformation monitoring. It also has important implications for future A0A deployments and in the perspective of the planned MARMOR seafloor cabled observatory.

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Since no significant vertical ground displacements have been recorded by ground GNSS stations since 2020, this study aims to assess the calibration method of the A0A system, reduce oceanic “noise” in corrected OBP records, and discuss the ability to observe any seafloor deformation offshore Mayotte. Numerical models, including ocean circulation (OGCMs) and barotropic models, were used to understand the influence of the different processes and to

reduce the oceanic “noise” in drift-corrected OBP records. Additionally, temperature and salinity data collected by repetitive glider transects were used to validate OGCMs in the region and quantify the contribution of unresolved processes to OBP records.

Our results provide valuable insights into the feasibility of using numerical modeling for improving the accuracy of OBP-based monitoring in the context of the Mayotte volcanic crisis as well as for other seafloor deformation monitoring. It also has important implications for future A0A deployments and in the perspective of the planned MARMOR seafloor cabled observatory.

JA04c - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Evaluation of the ability to extract crustal deformation signal from ocean bottom pressure time series using principal component analysis

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OBP (Ocean bottom pressure-gauge) is an essential sensor in crustal deformation observation in the marine region. Still, non-tidal oceanographic fluctuations in OBP data are a significant source of noise in seafloor transient crustal deformation observations, including SSEs (slow slip events), so it is essential to evaluate them properly. To extract and assess the significant characteristics of the oceanographic fluctuations, we applied PCA (principal component analysis) to the DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis, southwest margin of Japan) OBP time series of 40 stations for three years (2016–2019). PCA could separate several oceanographic signals based on the characteristics of their spatial distributions. The higher-order modes of the PC were distributed in a varying manner with sea depth, and we interpreted that they were caused by the strength and meandering of the ocean geostrophic currents based on similar spatial distribution with the global ocean models. Since PCA cannot detect the significant tectonic signal in observed data, we applied a synthetic ramp simulating SSE to the observation to evaluate the performance of PCA in tectonic signal detection. The assumed synthetic ramp could be separated into an independent principal component according to its amplitude (i.e., the scale of the events). We proposed a detection method of a transient event using the spatial distribution change of the principal component with and without the synthetic ramp using their normalized inner product. Our method was able to detect the tectonic signal of events of M_W5.9 or larger from the OBP time series.

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JA04c - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Monitoring fluid saturation in a gas-water system by utilizing CPET modelling of 4D seismic inversion results

DOI: 10.57757/IUGG23-0280 - LINK

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It is essential to comprehend how fluid concentration in rocks affects the hydrocarbon reserve and monitor fluid concentration for a sequestration or enhanced oil recovery programme. A prediction of saturation is highly uncertain due to the prior assumption that gas distribution is uniform or patchy in a rock physics theory. We therefore use the capillary pressure equilibrium theory (CPET) to develop a reservoir model that corresponds to the physics of capillary-induced fluid invasion and avoids the uncertainty associated with the type of gas distribution in pores. Assuming that the rock frame has not significantly changed throughout the field, we develop a CPET model utilising the reservoir parameters of the clean and unconsolidated sandstone formation of the Sleipner field, North Sea, which is the first industrial-scale CO_2-injection operation ever. The fluid content of the Sleipner field is then estimated by interpreting the time-lapse seismic inversion results using the model. According to our research, CO_2 is similar to a uniform distribution at higher concentrations, whereas it is mostly a somewhat patchy type at lower concentrations, or somewhere in between patchy and uniform distribution. Maximum CO_2 saturation is predicted using the CPET as 75% of the pore space. The topmost layer's CO_2-plume footprint is expanding from zero in 2001 to 7X105 sq. m. in 2010, according to a quantitative interpretation of six time-lapse seismic data sets from 1999 to 2010. Our model predicts that 50 years after the start of injection, CO_2 from all layers below will migrate to the top layer.

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JA04c - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Understanding Broadband Ocean Bottom Seismometer Noise: Fresh Insights and Future Directions

DOI: 10.57757/IUGG23-4779 - LINK

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The recent proliferation of broadband ocean bottom seismometer (BBOBS) deployments has generated datasets from diverse marine environments, improving our understanding of tectonics and earthquake processes. In turn, the community of scientists using this data has expanded. This growth in BBOBS data collection is likely to persist with the arrival of new seismic seafloor technologies, and continued scientific interest in marine and amphibious targets. However, the noise inherent in OBS data poses a challenge that is markedly different from that of terrestrial data. As a step towards improved understanding of the sources of variability in this noise, we present a new compilation and analysis of BBOBS noise properties from 15 years of US-led seismic deployments. We find evidence for similarity of noise properties when grouped across a variety of parameters, with groupings by seismometer type and deployment water depth yielding the most significant and interpretable results. Instrument design, that is the entire deployed package, also plays an important role, although it strongly covaries with seismometer and water depth. We find that the presence of tilt noise is primarily dependent on the type of seismometer used (covariant with a particular subset of instrument design), that compliance noise follows anticipated relationships with water depth, and that shallow, oceanic shelf environments have systematically different microseism noise properties (which are, in turn, different from instruments deployed in shallow lake environments). We discuss implications for the viability of commonly used seismic analysis techniques, and future directions for improvements in the efficiency of analysis of BBOBS data.

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JA04c - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Investigation of geoid gradients estimated from simulated SWOT altimeter data

DOI: 10.57757/IUGG23-3769 - LINK

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The recent Surface Water Ocean Topography (SWOT) altimeter mission measures two-dimensional SSHs along two 50-km-wide swaths and one-dimensional SSHs along the nadir track, providing a significant opportunity to improve the accuracy and resolution of geoid gradients essential for marine gravity modeling. This study investigates the accuracy of determining north and east components of geoid gradients using simulated SWOT SSHs in the northern part of the South China Sea. SWOT SSH data were simulated using ocean depths from multi-beam and the GEBCO_2020 bathymetry model and the DTU mean sea surface. According to the unique characteristic of high-resolution two-dimensional SWOT SSH observations, we developed a new method that determines north and east components of geoid gradient at the grid point based on geoid gradients computed in along-, cross- and middle-track directions using the least-squares adjustment (LSA). For comparison purpose, the gradient components were also computed using the least-squares collocation (LSC). The accuracy of determined gradient components is assessed using the quasi-true values of gradients computed by numerical differentiations from the SWOT simulation model. The RMSE results are 0.51 (0.42) microrad and 1.12 (0.91) microrad for LSA (LSC) estimates of north and east components, respectively, in the study area. The results indicate that the LSA gradient solution is computationally efficient and compatible with those by the LSC. The SWOT mission significantly improves the accuracy of estimated gradient components when compared to Jason-2 and Cryosat-2.

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JA07a - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Creation and evolution of the EMSEV working group - Its history and the role played by Professor Uyeda

DOI: 10.57757/IUGG23-0696 - LINK

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[3]*USGS, Earthquake Science Center, Menlo Park, USA*

EMSEV's first chairperson, Professor Seiya Uyeda passed away on January 19, 2023, at the age of 93. Electromagnetic monitoring of active faults and volcanoes was driven by hopes of predicting earthquakes and eruptions in the 1970s to the 1990s. Groups from many countries across the world installed instruments and the newly obtained results were presented at many meetings (IUGG, IASPEI, IAGA, IAVCEI, AGU, etc.).

These new efforts also led to many lively discussions by groups of researchers on the future formation of an Electromagnetic Studies Working Group to bring together isolated researchers located in many different countries throughout the World. Prof. Seiya Uyeda was one of the most active leaders in this field.

The discussion started anew during the 1999 International IUGG GA in Birmingham (UK). This time, Prof. Uyeda's breakthrough concept was to build a joint Inter-Association (IAGA, IASPEI, and IAVCEI) Working Group to link these isolated scientific groups for developing interconnected field research. Finally, the recommendations were submitted to the IUGG Executive Committee to form an inter-association Working Group focused on a common understanding of the physical processes related to earthquake ruptures and volcano eruptions. Thus, the EMSEV (Electromagnetic Studies of Earthquakes and Volcanoes) Working Group was born.

Since then, EMSEV has continued to be active, holding its own general meeting every two years and contributing to the development of electromagnetic research. In the presentation, we would like to praise Professor Uyeda's achievements and introduce the role that EMSEV has played in this field.

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JA07a - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

The new frontier of satellite pre-earthquake signal detection: the cases of Swarm and CSES missions

DOI: 10.57757/IUGG23-1719 - LINK

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[1]Istituto Nazionale di Geofisica e Vulcanologia, Environment Department, Roma, Italy
[2]Universidad Complutense de Madrid, Department of Physics, Madrid, Spain
[3]Istituto Nazionale di Geofisica e Vulcanologia, Earthquake Department, Roma, Italy

De Santis et al. (EPSL 2017) detected that for the first time in Swarm satellite data some magnetic field anomalies associated with the 2015 Nepal M7.8 earthquake, with similar S-shapes for the cumulative number of satellite anomalies and earthquakes, providing an empirical proof on the lithospheric origin of the anomalies. Following the same approach, De Santis et al. (Atmosph. 2019) obtained other promising results for 12 earthquakes in the range M6.1-8.3, in the framework of the ESA funded SAFE (SwArm For Earthquake study) Project. Then, almost five years of Swarm magnetic field and electron density data were analysed with a Superposed Epoch and Space approach finding a robust correlation with major worldwide M5.5+ earthquakes (De Santis et al. Sc.Rep. 2019). The work also confirmed the Rikitake (1987) law, initially proposed for ground data: the larger the magnitude of the impending earthquake, the longer the precursory time of anomaly occurrences. An analogous analysis was also applied in the framework of the ASI funded Limadou-Science Project to the Chinese Seismo-Electromagnetic satellite (CSES) electron density providing similar results (De Santis et al. N.Cim. 2021). Marchetti et al. (Rem.Sens. 2022) confirmed the same result over a longer time series , i.e. 8 years, of Swarm satellite data. Furthermore, we demonstrated in several case studies (e.g. Marchetti et al. JAES 2019, Akhoondzadeh et al. Adv.S.R. 2019; De Santis et al. Fr.E.Sc. 2020) that the integration of CSES and Swarm data with other measurements from ground an atmosphere reveals a chain of processes before many mainshocks.

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JA07a - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Recent topics on the ionospheric changes immediately before large earthquakes

DOI: 10.57757/IUGG23-1037 - LINK

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Densification of continuous GNSS (global navigation satellite system) networks enabled us to observe changes in ionospheric TEC (Total Electron Content) associated with large earthquakes. Here I focus on anomalies immediately before M8-9 class earthquakes. Such preseismic anomalies were first found after the 2011 Mw9.0 Tohoku-Oki earthquake (Heki, 2011 GRL) and later for all the earthquakes in this century with Mw 8.2 or more (Heki & Enomoto, 2015 JGR; He & Heki, 2017 JGR). ~20 examples exhibit scaling laws, (1) leading times range from ~15 minutes (M8) to ~45 minutes (M9) and scale with fault lengths, and (2) anomaly strengths range from ~1 % (M8) to ~10 % (M9) of the background values and scale with fault areas. 3D tomography (Muafiry & Heki, 2020 JGR) showed that the positive/negative anomalies grow simultaneously at low/high altitudes above land and line-up along the geomagnetic field, suggesting crustal electric field responsible for the electron redistribution. Here I also report a few new examples not well studied before, e.g., the 2008 Wenchuan earthquake in China and the 2023 February 6 earthquake in southern Turkey. One difficulty in using this information for practical short-term earthquake forecasting would be its discrimination from space weather origin disturbances. I present a case immediately before the 2022 eruption of the submarine volcano in Tonga. A typical "pre-eruption" ionospheric changes were found, but I demonstrate it was a fake precursor caused by space weather.

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JA07b - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Co-seismic Ionospheric Disturbances Observations and Lithosphere-atmosphere-Ionosphere dynamic modeling

DOI: 10.57757/IUGG23-4364 - LINK

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Large and shallow earthquakes (minimum magnitude 6.5) generate distinctive ionospheric disturbances detectable using radio signals emitted by Global Navigation Satellite Systems (GNSS). In the recent years, the number of satellites has increased drastically, allowing a refined coverage of the Earth, including the earthquake-prone zones. The subduction zones (e.g. Japan, Indonesia, South America), where most tsunamigenic earthquakes occur, are poorly instrumented because located offshore, far from the coasts. By measuring the integrated quantity of electrons along the satellite-receiver paths, the Total Electron Content (TEC), GNSS satellites offer the capability to sound the ionosphere in all directions, including far from the receiver when satellites can be tracked at low elevation. Besides the enhanced coverage, we further investigate the new capabilities carried out by the new frequencies (L5, E5) offered by the US Global Positioning System (GPS), the European Galileo as well as the Indian Regional Navigation Satellite System (IRNSS) for seismic source studies. We investigate past earthquakes with a multi-GNSS scenario and discuss how such observations can be usefully included in tsunami early-warning systems for the case of an underwater earthquake poorly instrumented. More specifically, we study the morphology of co-seismic TEC signatures derived from numerical modeling results of seismo-acoustic waves. Simulated using an acoustic ray tracing method, atmospheric perturbations are coupled with the ionospheric plasma through transport mechanism by the local geomagnetic field. The electron density perturbation is finally integrated along the known satellite-station line-of-sights, based on the information of GNSS satellite orbits.

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JA07b - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Lithosphere-Atmosphere-Ionosphere coupling: CSES achievements and IMCP prospects

DOI: 10.57757/IUGG23-1286 - LINK

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Being the first geophysical fields observation satellite mission, CSES-01 has operated for 5 years as scheduled by Feb.02, 2023 and on the basis of its fine performance, CSES-01 will prolong its life until CSES-02 lunching in orbit and collaborative work each other in orbit.

The last 5 years, in retrospect, CSES-01 acquired an amount of data such as geomagnetism field, low frequency electromagnetic waves, in-situ plasma content and temperature, charged particles as well ionospheric plasma CT, in which, more than 50 earthquakes with magnitude greater than 7 and 500 greater than 6 are recorded in globe, together with a series of space weather and volcano phenomenon were recorded. So far, we result positive knowledge on earthquake precursors according to the statistical research and case study of most of these events, and develop the Lithosphere-Atmosphere-Ionosphere Coupling mechanism focusing on its electromagnetic wave channel.

The following prospect plan, CSES-02 is under developing by China-Italy joint team and is due to launch in 2024, which means that we'll have 2 CSES satellites in orbit from 2024. Now we're demonstrating the new mission of IMCP-International Meridian Circle Project, which should be a ground-based observation network with its main objectives on monitoring the geomagnetical field, space weather and interaction among Lithosphere-Atmosphere-Ionosphere. And the main tasks of IMCP are global data sharing, joint research on space weather and natural hazards as well global change, and so on.

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JA07b - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

The interaction of electric field in LAI coupling mechanism around strong earthquakes in China

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The electromagnetic satellite observations show typical advantages in short-term earthquake prediction due to the strong ionospheric perturbations before earthquakes in 1 week, but the coupling mechanism among lithosphere-atmosphere-ionosphere (LAI) is still a big problem to be faced. Based on the previous models in LAIC, it is found that electric field in atmosphere and ionosphere play significant roles in the coupling processes. Since the launching of CSES in 2018, it has operated for 5 years unitl now. During this time period, there occurred more than 10 earthquakes with magnitude larger than 6 in China, where the biggest one is Maduo Ms7.4 earthquake in May 2021. Around these earthquakes, a lot of disturbances have been detected by satellite and ground based electromagnetic observations. The closer the time to the occurrence time of earthquakes is, the more the parameters with disturbances occurred. 3 or 4 parameters exhibited anomalies simutaneously within 2 weeks or just 1 week prior to half of the earthquakes, to illustrate the close relationship among them. Taking an example, the Yangbi Ms6.4 and Maduo Ms7.4 occurring successively in 4 hours on 21 May 2021 was analyzed in detail. And the electric field in atmosphere and ionosphere was focused on with the observations at ground and satellite. It is concluded that: (1) The atmospheric electric field is illustrated with upward disturances in epicentral region; (2) The relationship between atmospheric electric field with ionospheric electric field and other plasma parameters was validated to improve the reliability of anomaly detection before earthquakes.

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JA07b - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Multi-instrument surveying for pre-earthquake transient features of atmosphere-ionosphere. Case studies for 2021 – a year of global seismic unrest

DOI: 10.57757/IUGG23-3151 - LINK

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[5]Department of Earth Sciences- Graduate School of Science, Chiba University, Chiba, Japan
[6]National Institute of Natural Hazards, Data Center, Beijing, China
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We present a multi-parameter study of transient phenomena observed in the Earth's atmosphere-ionosphere environment plausibly associated with the latest major seismic activities in 2021. The year 2021 was the most active period for global seismicity since 2007, with 19 major earthquakes (M7+), three of which were over M8.0. The M 7.2 in Haiti was the deadliest for 2021, with 2,476 fatalities (USGS).

We monitored critical processes in the atmosphere /ionosphere that modify the Earth's plasma environment system under various geophysical conditions, including earthquakes. We collected operational data from several instruments:1. Electric field and plasma observations from the China/Italy Seismo-Electromagnetic Satellite (CSES1); 2/ Outgoing long-wavelength radiation (OLR) obtained from NPOESS); 2/ Atmospheric chemical potential (ACP) obtained from NASA assimilation models; and 3/ Electron density variations in the ionosphere via GPS Total Electron Content (GPS/TEC).

We observed a synergetic abnormal response of satellite OLR data, plasma data from CSES, and GPS/TEC and ACP starting two weeks before the M 8.1 - South Sandwich; M 8.2 – Alaska, US; M 8.1 - Kermadec Islands, NZ, and M 7.2 - Nippes, Haiti earthquake. Our integrating data search reveals different abnormal patterns inside the Dobrovolsky-Bowman estimating earthquake preparation zone. We show that by combining the near-space and ground data accordingly to the physical concept of the Lithosphere-Atmosphere-Ionosphere Coupling (LAIC), we could identify, on a regional basis, abnormal patterns of pre-earthquake-related features in the atmosphere-ionosphere environment. The implications of studying major earthquake events are discussed.

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JA07c - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Spatial analyses on seismo-ionospheric anomalies of total electron content before the 6 February 2023 M7.8 and M7.5 Turkey Earthquakes

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On 6 February 2023 at 01:17 UTC, an M7.8 earthquake occurred in South-Eastern Turkey (37.2°N 37.0°E, 10.0 km depth), and several strong aftershocks have also been observed in the region, notably a magnitude M7.5 (38.0°N 37.2°E, 10 km depth) at 10:24 UTC the same day. Spatial analyses of the total electron content (TEC) of the global ionosphere map (GIM) are employed to observe the latitude-longitude distributions of seismo-ionospheric anomalies (SIAs) during January-February 2023. A global search of 5183 (=73x71) lattices shows that SIAs of significant TEC increases specifically appear near the epicenter on day 24-22 (12-16 January) and 2-0 (4-6 February) before the two earthquakes. The ion density and ion velocity measured by the science payload of Advanced ionospheric Probe (AIP) onboard the FORMOSAT-5 (F5) satellite and the EIA (equatorial ionization crest) distances between northern and southern hemispheres of GIM TEC are used to find the ionospheric electric fields over the epicenter area during the two periods of 12-16 January and 4-6 February 2023.

https://earthquake.usgs.gov/earthquakes/eventpage/us6000jllz
https://earthquake.usgs.gov/earthquakes/eventpage/us6000jlqa

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JA07c - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Long-term (2004-2022) analysis of TIR anomalies over Turkish area: the case of Kahramanmaraş (February 6th 2023, M7,8) EQ

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[1]*University of Basilicata, School of Engineering, Potenza, Italy*
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A long-term (2004-2015) analysis of the fluctuations of Earth's thermally emitted radiation, measured by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the Meteosat Second Generation (MSG) satellite in the thermal infrared (TIR) spectral range (i.e. 10-12 μm), have been performed in order to investigate the complex process of preparation of earthquakes in that area.

Such analysis showed that more than 67% of all identified (space-time persistent) anomalies occur in the pre-fixed space-time window around the occurrence time and location of earthquakes (M≥4), with a false positive rate smaller than 33%. Moreover, Molchan error diagram analysis gave a clear indication of non-casualty of such a correlation, in comparison with the random guess function.

In this paper, the characterization of the signal, in terms of punctual expected values and related variability, have been extended up to 2022 and the Robust Satellite Technique (RST) and RETIRA (Robust Estimator of TIR Anomalies) index applied to identify possible Significant Sequences of TIR Anomalies (SSTAs) in 2023 in relation with the seismic sequence that hit the region of Kahramanmaraş starting with the February 6th, M7,8 EQ.

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JA07c - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Multi-parameter ground and space observation of pre-earthquake signals associated with the Earthquake sequence in Turkey, February 6th, 2023

DOI: 10.57757/IUGG23-4121 - LINK

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Institute for Earth- Computing- Human and Observing Institute for ECHO, Orange- CA, USA
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[4]National Institute of Natural Hazards, CSES Data Center, Bejing, China
[5]Institute of Geonics, Czech Academy of Sciences, Ostrava, Czech Republic

On Feb 6, 2023, M7.8 and M7.5 earthquakes struck Turkey within 9 hours difference, and with a more than 100 km rupture, were the deadliest earthquakes in Turkey/Syria this decade. We study critical lithosphere/atmosphere /ionosphere coupling processes that precede earthquake events. We combine observations from non -correlated ground and space monitoring systems for the first time, such: 1/ Vertical static pendulums data from the European network; 2/ Outgoing long-wavelength radiation (OLR) obtained from NPOESS; 3/ Ionospheric plasma observations from China/Italy Seismo-Electromagnetic Satellite (CSES1); and 4/ Atmospheric chemical potential (ACP) obtained from NASA assimilation models. The deformation anomalies started at all European pendulum instruments on Jan 23, 2023. The most significant anomaly was recorded in cave No.13 (the Moravian karst). The pendulum is located on the N-S-oriented fault corresponding to the East Anatolian Fault activation (NE-SW). NOAA satellite thermal observations of the epicentral area show an increase in infrared radiation starting in Dec 2022 and riches the maximum on Jan 13 and Feb 1, 2023, near the epicentral area. Increases in OLR from the satellite data coincided with an intensification in the atmospheric chemical potential, Feb 1-4, measured near the epicentral area. The plasma electron and oxygen ion density from the CSES1 satellite showed an abnormal increase on Jan 27-28, which is highly correlated with the earthquake occurrence given the stable space weather index during this period. We show that by combining ground and near-space data accordingly to the physical concept of LAIC, we could identify abnormal patterns of pre-earthquake-related features.

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JA07c - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Spatial and Temporal Characteristics of Ionospheric Electron Density Distribution related to the Pre-Seismic and Geomagnetic Storm Cases over Japan

DOI: 10.57757/IUGG23-3713 - LINK

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The ionospheric anomalies possibly associated with large earthquakes have been reported by many researchers. In this paper, Total Electron Content (TEC), Ionosonde, and tomography analyses have been applied to investigate the spatial and temporal anomalies of ionospheric electron density prior to the 2011 Off the Pacific Coast of Tohoku earthquake (Mw9.0). Results show significant TEC enhancements and an interesting three dimensional structure prior to the main shock. As for temporal TEC changes, the TEC value increases 3-4 days before the earthquake remarkably, when the geomagnetic condition was relatively quiet. In addition, the abnormal TEC enhancement area in space was stalled above Japan during the period. Tomographic results show that three dimensional distribution of electron density decreases around 250 km altitude above the epicenter (peak is located just the east-region of the epicenter) and increases the mostly entire region between 300 and 400 km. Details and statistical tendency and differences from the case of geomagnetic storms will be also shown in our presentation.

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JA07c - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Coupling of natural hazards events with the ionosphere inferred from ground VLF/LF electric- and satellite magnetic-field measurements

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[2]Space Observation Research Center, National Institute of Natural Hazards, Beijing, China
[3]Institute of Experimental Physics, Graz University of Technology, Graz, Austria
[4]Institute of the Earth Physics, Russian Academy of Sciences, Moscow, Russian Federation
[5]Physics Department, Università di Bari, Bari, Italy
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Strong natural hazards events are assumed to be significant sites to investigate the lithosphere-atmosphere-ionosphere coupling (LAIC), showing possibly a multitude of processes up to high altitudes. Until now there is no clear consensus on how specific mechanisms affect the different layers and important questions persist.

In this study we analyse European earthquake events with magnitudes M ≥ 5 based on the USGS catalogue, a second focal point is a particular class of volcanic eruptions selected from Mt. Etna (Sicily, Italy) activity periods.

We examine electric field variations in the earth-ionosphere waveguide along radio paths between narrowband VLF/LF transmitters and ground-based receiver facilities (INFREP network). Those observations are combined with in-situ satellite magnetic field measurements from the missions Swarm and CSES-1 at LEO altitudes. For both investigations spatio-temporal proximity to the event sites is necessary. The selected bundling of the two field parameters enables the steady VLF/LF electric-field measurements from the lithosphere up to the ionospheric D/E-region and the satellite measurements assess parts at the end of the propagation channel in the ionospheric F-region at about 500 km altitude.

Results for volcanic eruptions show a decrease in the VLF/LF electric fields of up to 10 dB with fluctuations in the frequency range of atmospheric gravity waves (AGWs). Earthquakes exhibit larger VLF/LF amplitude values after the event (night-time amplitude method). We find no clear signatures in the ionospheric satellite magnetic field measurements, but future missions like CSES-2 double the revisiting frequency above natural hazards prone areas and will facilitate further in-detail investigations.

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JA07c - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Probing normal mode signals with seismological and ground-based atmospheric observations

DOI: 10.57757/IUGG23-2554 - LINK

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In normal mode seismology, the atmosphere and the solid Earth are generally considered to be decoupled, and the seismic wave energy from the Earth's interior is difficult to propagate into the atmosphere. However, a growing number of studies have shown that earthquakes, volcanoes and tsunamis can disturb the Earth's atmosphere due to various coupling effects. Therefore, it is an open question whether normal mode (especially in low frequency) signals can be detected in atmospheric observations. In our study, experiments were conducted to investigate the existence of normal mode signals in surface atmospheric observations using the improved multi-taper method, based on the seismographs and ground-based atmospheric observations of the Global Seismic Network before and after the 2021 Mw8.2 Alaska earthquake. Then, the results showed that the normal mode signal can be detected in the pressure observations by comparing the pre-earthquake, post-earthquake and theoretical calculations. However, since the signal-to-noise ratio varies greatly between stations and modes, direct correction of the barometric pressure by the admittance method may lead to large deviations in the estimation of normal mode parameters. Furthermore, we investigate the generation mechanism of seismic normal modes in surface atmospheric observations, which suggests that these signals originate from crust-atmosphere coupling in the same frequency band, and this possible coupling should be considered in normal mode seismology research.

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JA07d - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Detection of electromagnetic anomalies over seismic regions during strong (MW > 5) earthquakes

DOI: 10.57757/IUGG23-0159 - LINK

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[1]University of Trento, Physics Department, Povo, Italy
[2]National Institute of Astrophysics, Institute of Astrophysics and Planetology, Rome, Italy
[3]National Institute of Nuclear Physics, Tifpa, Trento, Italy
[4]University of L'Aquila, Disim, L'Aquila, Italy
[5]University of L'Aquila, Dsfc, L'Aquila, Italy

Over the last few years, the scientific community has made a significant effort to detect and interpret electromagnetic signals that might be related to seismic activity. Recent studies have shown how during or even before strong earthquakes the ionosphere shows characteristic electromagnetic interactions observed as plasma variations or electromagnetic (EM) emissions (both in the ELF and VLF bands). These EM emissions were detected both by ground-based [Pulinets and Boyarchuk 2004] and by space-based [Ouzounov et al. 2011, Pulinets and Ouzounov, 2011] instruments.

However, a robust identification of such EM emissions should start from the definition of statistical distribution of the ionospheric electromagnetic (EM) waves energy in absence of seismic activity and other anomalous inputs (such as the ones derived by solar forcing). In this way, a background in the ionospheric EM emissions over seismic regions can be determined. Only after this step, a proper detection of an EM signal possibly correlated with the seismic activity can be accomplished: every EM signal which differs from the background (exceeding a statistically meaningful threshold) should be considered as a potential event to be investigated.

Therefore, in this study, we performed a multiscale analysis of the ionospheric environmental background, using the entire CSES-01 (China Seismo-ElectroMagnetic Satellite) electric and magnetic field dataset (2018 - 2023), by creating the map of the averaged relative energy (ε_{rel}) over a 1° x 1° latitude-longitude cell, depending on both spatial and temporal scale of the ionospheric medium. The analysis was performed by means of the newly developed Fast Iterative Filtering (FIF) technique.

Geomagnetic activity conditions are considered by the means of the Sym-H index in order to make a proper discrimination between external (atmospheric, ionospheric, magnetospheric, solar and cosmic activities) and internal (earthquakes, volcanoes) sources generating anomalous signals.

Here we present the background obtained for various seismic regions and results obtained for some recent earthquakes.

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JA07d - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

The effects of the geospace environment on solar-lithosphere coupling and earthquake processes

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We study the space weather variations like magnetic storms and their impact on earthquake processes. We have found that about two months after creating a new radiation belt in the inner magnetosphere due to a geomagnetic storm, an increasing seismic activity may occur near the magnetic field lines' footprint of a newly created radiation belt. The Combined Release and Radiation Effects Satellite (CRRES) detected a new radiation belt after a geomagnetic storm on March 24, 1991. Shortly after that, on May 30, 1991, a strong M7.0 earthquake occurred in Alaska in the footprint of geomagnetic line L~2.69. Additionally, on October 28, 2012, a strong M7.8 earthquake occurred in Canada near the footprint of L~3.3, which was close to the magnetic lines of a new radiation belt detected by a satellite "Van Allen Probes" after a geomagnetic storm on September 3, 2012. We demonstrate the possible existence of two ways of solar-lithosphere coupling processes: (i) the disturbances in the lithosphere accompanying the earthquake preparation process can modify the electric field in the global electric circuit (GEC), and the vice-versa mechanism, (ii) the solar wind-generated disturbances in the magnetosphere and ionosphere, can modify the electric field in the GEC, that will result in appearing of disturbances in the lithosphere.

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Identification of Cianjur active fault using magnetotelluric method

DOI: 10.57757/IUGG23-3867 - LINK

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An in-land earthquake of magnitude 5.6 struck Cianjur, West Java, Indonesia on November 21, 2022, at 13.21 local time causing severe damage with at least 602 deaths and the destruction of 58.000 houses. The mainshocks–aftershocks analysis suggests that the earthquake resulted from an unmapped fault with a debatable strike orientation. To investigate the subsurface structure of the affected region, we conduct a magnetotelluric (MT) survey, which has been shown to effectively image the faults at the deep subsurface level. In this study, four magnetotelluric stations were installed along a 3 km line profile through the earthquake epicenter with an acquisition time of approximately 20 hours. The MT soundings 2-D modeling inversion results show the resistivity contrast along the profile, revealing the low-resistivity zone interpreted as the existence of an unmapped fault with a depth of up to 10 km that is most probably correlated with the earthquake's hypocenter location. Our findings also provide valuable insights into identifying weak zone in the region for further analysis and seismic hazard assessment.

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Anomalous signatures in geomagnetic field - with reference to local earthquakes from Kuchch. India

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The Kachch region of western India is characterized by multiple intraplate seismic sources in the form of several east-west trending faults. A 7.6 magnitude earthquake occurred near the city of Bhuj here in 2001 resulting in severe loss of life and property. Seismicity in this area continues with several moderate crustal earthquakes of 3.5-4.5 magnitude occurring each year. Studies to identify precursors, were initiated in 2009. Geomagnetic data from magnetic observatory at Desalpar (DSP) situated near to the Kachchh Mainland Fault in close proximity to the seismic cluster, is examined for anomalous signatures associated with lithospheric process. The diurnal variations in the geomagnetic Z component (ΔZ) have been studied for the duration of 2010-2018 to extract anomalous signatures, after removing seasonal effects. Effects of ionospheric and magnetospheric phenomena are also eliminated. The residual anomalous signatures in ΔZ are attributed to lithospheric origin. Such anomalies in ΔZ are observed 2-5 days before the earthquakes, on an average.

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JA08a - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

RASE: A real-time automatic search engine for anomalous seismic electric signals in geoelectric data

DOI: 10.57757/IUGG23-2227 - LINK

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The geoelectric data contain important anomalous information for short-term earthquake prediction. Timely and accurate identification of seismic electric anomalies is important for disaster prevention. However, identifying anomalies is challenging due to the huge volumes of data and noise disturbance. In this study, we develop a real-time automatic search engine (RASE) that incorporates an unsupervised convolutional denoising network (UCN) module and a supervised LSTM network (SLN) prediction module to automatically search for important anomalous signals in real-time. Experiments demonstrate that the RASE provides excellent detection accuracy and efficiency for synthetic and field data, which takes only dozens of seconds for a common PC to provide accurate detection results for data collected over a 24-hour period. The RASE has excellent flexibility and developability, as its internal modules can be adapted by more suitable technologies for better performance in various application scenarios. Comparison of multiple module combinations shows that the RASE configured with UCN and SLN has the highest detection accuracy. Our proposed search engine can reduce the human labor required for complex and repetitive detection work and fully realize the potential of geoelectric field observation in earthquake monitoring and disaster prevention.

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JA08a - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Deep Electrical Resistivity Tomography for investigating seismic and volcanic areas: State-of-the-art and future directions

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Electrical Resistivity Tomography (ERT) is a robust and well-consolidated method largely applied in near-surface geophysics. Nevertheless, the mapping of the spatial resistivity patterns of the subsurface at a depth greater than 1 km was performed in just a few cases by the ERT method, called deep ERT (DERT). Information on the electrical properties of the rocks beyond ~1 km depth has been obtained only from direct soundings or passive electromagnetic measurements (e.g., Magnetotelluric—MT) so far. In this work, a critical review of the recent results obtained during geophysical field surveys carried out with the DERT method is presented. The limits and the advantages related to the application of the DERT method in the geophysical exploration of seismic and volcanic areas are identified and discussed. The study focuses both on the purely methodological aspects (e.g., geoelectrical data processing in low noise-to-signal ratio conditions; 2D and 3D tomographic algorithms for resistivity data inversion) and on the technological features (e.g., sensor layouts, multi-array systems). Furthermore, great attention has been devoted to the novel applications of the AI-based methods and machine learning for geoelectrical data processing. The results of this work envisage the possibility of studying geophysical problems that are still unsolved and/or poorly studied in seismic and volcanic areas, as the fluid and gas migration from deep geological environments. Finally, future research directions are identified and discussed.

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JA08a - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Magnetotelluric imaging for fluids in the crust and upper mantle beneath the southern part of Northeast Japan subduction zone

DOI: 10.57757/IUGG23-0773 - LINK

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[1]The University of Tokyo, Earthquake Research Institute, Tokyo, Japan
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Northeast Japan is one of the world's most active subduction zones, having great earthquakes and volcanic eruptions, such as the M9.1 Tohoku Earthquake in 2011. Efforts to understand the subsurface structure via magnetotelluric studies have been extensive because electrical resistivity is sensitive to fluids in the crust and upper mantle. As a result, the deep, regional resistivity structure has been obtained beneath the northern and central parts of Northeast Japan (Ogawa et al., 1986; Ichiki et al., 2015). In this study, we aimed to image the southern part. This area has quaternary volcanoes on the backbone range and the back-arc side, active deformation regions, and shallow to deep seismic activities. Such activities are generally viewed to be caused by fluids in the crust and upper mantle that originated from the subducting slab (e.g., Iwamori, 1998; Wallace, 2005). So, we performed a wide-band magnetotelluric study by deploying electromagnetic field recording stations on three parallel NW-SE profile lines across the island arc. Each line consists of about 15 stations with nearly 10 km intervals. We estimated the MT impedance, vertical magnetic field transfer function (VMTF), and inter-station horizontal magnetic field transfer function (HMTF) at periods 0.03 - 13,000 seconds using the BIRRP code (Chave and Thomson, 2004). FEMTIC inversion code (Usui, 2015; Usui et al., 2017) was used for three-dimensional inversion because it can jointly invert the three response functions. In the presentation, we discuss the resulting resistivity structure and its correlation with active volcanoes and seismic activities.

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JA08a - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Measurement of total magnetic intensity at MT. Fuji for volcanic eruption prediction research

DOI: 10.57757/IUGG23-0704 - LINK

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[2]*University of Shizuoka, Global Center for Asian and Regional Research, Shizuoka, Japan*
[3]*The University of Tokyo, Earthquake Research Institute, Tokyo, Japan*

As is well known, the last eruption of Mt. Fuji was the Hoei eruption in 1707, and there has been no eruption for more than 300 years. It is common knowledge in volcanology that Mt.Fuji is a very young volcano and it is 100% certain that an eruption will occur in the future. Because of its proximity to the Tokyo metropolitan area, it is believed that an eruption would cause enormous damage to Japan, which has become IT-oriented.

In October 2020, our group set up a permanent total magnetism observation point at an altitude of 1400m, which will serve as a reference point for future geomagnetic observations.

In evaluating observation data, in order to judge whether it is an artificial change due to a physical change in the position of the sensor (sensor pole tilted due to force majeure, etc.) or a true change in the natural world is very important. Therefore, in the summer of 2022, we conducted geomagnetic preliminary observations from the summit to the vicinity of the 6th station and succeeded in selecting candidate sites for future permanent observation points.

In the future, we intend to conduct electromagnetic monitoring of Mt. Fuji as the IUGG-EMSEV project.

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JA08a - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Evidencing fluid migration of the crust during the earthquake cycle by using 1D-magnetotelluric monitoring

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[1]*Universidad Nacional de Colombia, Departamento de Geociencias, Bogota, Colombia*
[2]*Universidad Nacional de Colombia, Department of Geosciences, Bogota, Colombia*
[3]*Universidad de Buenos Aires, Instituto de Astronomía y Física del Espacio- CONICET, Buenos Aires, Argentina*
[4]*Universidad Nacional de Colombia, Department of Physics, Bogota, Colombia*

We apply multi-temporal 1D-magnetotelluric (MT) surveys to identify space-time anomalies of apparent resistivity in the upper lithosphere in the Antarctic Peninsula (border between the Antarctic and the Shetland plates). We use time series over several weeks of the natural Earth's electric and magnetic fields registered at one MT station of the Universidad Nacional de Colombia (RSUNAL) located at Seymour – Marambio Island, Antarctica. We associate resistivity anomalies with contrasting earthquake activity. Anomalies of were detected almost simultaneously with the beginning of a seismic crisis in the Bransfield Strait, south of King George Island (approx. 85.000 events were reported close to the Orca submarine volcano, with focal depths < 20 km and $m_b < 6.9$). We explain the origin of these anomalies in response to fluid migration near the place of the fractures linked with the seismic swarm, which could promote disturbances of the pore pressure field that reached some hundreds of km away.

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JA08a - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

On the possible relation between characteristic EM variations and aftershocks of the 2016 Central Tottori earthquake

DOI: 10.57757/IUGG23-1387 - LINK

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[3]*Kyoto University, Disaster Prevention Research Institute, Kyoto, Japan*

There are many reports on variations in the electromagnetic (EM) field in association with occurrence of earthquakes. However, the reliability of their existence is still a topic of dispute. It should be tested by referring many events to secure the statistical significance. In the present study, we referred EM dataset acquired just after the 2016 Central Tottori earthquake. The data were originally recorded for the EM sounding around the focal area. The characteristic variations in the EM time series were tried to be identified and the timing of their occurrence was compared with the aftershocks to confirm the hypothesis that variations in the electromagnetic do occur in association with earthquakes. To perform an exhaustive and objective counting, we proposed an automatic procedure to detect EM signals in the time series. A template waveform was defined by stacking representative waveforms that were picked up by visual inspection. The EM signals were identified by comparing the EM time series and the template waveform. By using the proposed procedure, we confirmed that the number of signals occurred during a several time-range before and after earthquakes are larger than that expected when it occurred randomly. We also performed a statistical test for the increase in the signal occurrence rate and confirmed that the recognized increase in the signal occurrence rate was significance with the 95% reliability. These results suggest that EM variations recorded in the EM time series include earthquake-related signals, at least for the case of aftershocks of the 2016 Central Tottori earthquake.

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JA08b - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Ionospheric seismology and volcanology

DOI: 10.57757/IUGG23-0316 - [LINK]

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Large earthquakes and volcanic eruptions disturb ionosphere in various ways, and we can observe them with global navigation satellite system receivers as changes in total electron content (TEC), number of electrons along the line-of-sights connecting the receivers and the satellites. I first review ionospheric disturbances related to earthquakes. They appear ~10 minutes or later after earthquakes as sudden TEC changes propagating with three different speeds, ~4 km/s (Rayleigh wave), ~0.8 km/s (direct acoustic wave), and ~0.25 km/s (internal gravity wave). The disturbances caused by direct acoustic waves from the epicenters are useful to estimate moment magnitudes of earthquakes, although we should take care of the influences of geomagnetic fields and line-of-sight geometries on the observed amplitudes. Slow fault slip signatures were recently found to emerge as the large amplitudes of internal gravity wave signals relative to those by acoustic waves. Secondly, I discuss ionospheric TEC changes by large volcanic eruptions. They emerge in two distinct forms, long-lasting harmonic oscillations or short impulsive changes, often associated with Plinian continuous eruptions and Vulcanian explosive eruptions, respectively. In both types, disturbance amplitudes normalized by background vertical TEC provide useful measures of the eruption intensities. I also review observations of ionospheric responses to the 2015 January eruption in Tonga, where several brand-new TEC changes have been observed, e.g., the Lamb waves circulating the Earth multiple times, long-lasting harmonic oscillations caused by atmospheric modes, and sudden electron depletion possibly by the injection of water vapor molecules into the upper atmosphere.

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JA08b - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Locating the Tsunami Initiation Area Linked to the 2010 M7.7 Mentawai Earthquake from First Arrivals Measurements on TEC Data

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Forecasting the impact that a tsunami might have on the coastal areas requires accurately locating where the tsunami has been initiated. This is especially challenging since tsunamis often start far from seismological and geodetic networks. However, tsunami waves often induce ionospheric Total Electron Content (TEC) disturbances that can be detected by using Global Navigation Satellite Systems (GNSS). Tracing where these disturbances come from makes it possible to retrieve the initiation area of the tsunami. Previous studies have tested this approach. Still, it is generally done using (1) a 'quasi-homogeneous' model to propagate the disturbances within the atmosphere and (2) arbitrarily fixing the height of the ionosphere. These approximations lead to relatively large uncertainties about the location of the initiation area of the tsunami. This is why, in this study, we attempt to check if using a 1D model for the atmospheric structure can reduce these uncertainties and by including in the inverse problem the search for the optimal height of the ionosphere. To do so, we use a Bayesian approach to invert the onset times of the TEC disturbances. At first, we test our method on synthetic data to determine the potential gain in accuracy between using a 'quasi-homogeneous' and a 1D-model for the atmosphere. Then, we apply our approach to study the 2010 M7.7 Mentawai tsunami earthquake. Finally, we discuss how we envision including such data in future tsunami early-warning systems.

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JA08b - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

The challenge of investigating ionospheric perturbations connected to the 2020 Samos earthquake and tsunami

DOI: 10.57757/IUGG23-3931 - LINK

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The ability to issue timely tsunami warnings is a key challenge in GNSS Ionospheric Seismology research.

In this context, Total Electron Content (TEC) estimates represent an important parameter to sound the ionosphere using Global Navigation Satellite Systems (GNSS) observations. Earthquakes and tsunamis are, indeed, known to generate acoustic and gravity waves (AGWs), able to reach the ionosphere and cause perturbations in TEC values, known as Travelling Ionospheric Disturbances (TIDs).

In this study, we use the VARION algorithm, able to estimate TEC variations in real time, to investigate the eventual TIDs connected to Mw 7.0 Samos earthquake (37.8360° N 26.8080° E) that occurred on 30 October 2020. We employ 10 GNSS receivers from the Turkish and Greek networks (respectively TUSAGA-Akitf and HEPOS). We consider both raw and filtered VTEC variations. Specifically, we adopt bandpass and polynomial filters. We highlight small TEC variations possibly linked to the passage of acoustic-gravity waves. Spectral analysis shows peak frequency around 1-2 mHz.

The challenge of this study is, indeed, to eventually retrieve and highlight small amplitude TEC variations connected to the earthquake and tsunami. To this aim, we also use tide gauges (IOC_UNESCO) data to retrieve information on the tsunami waves.

In conclusion, the obtained results emphasize the importance of using GNSS ionospheric data to study and complete other known methods used for tsunami hazard estimation in the Mediterranean Sea.

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JA08b - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Ionospheric response to the 2020 Samos Earthquake

DOI: 10.57757/IUGG23-1938 - [LINK]

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Institute for Astronomy- Astrophysics- Space Applications & Remote Sensing, Athens, Greece

On 30 October 2020 at 11:51 UT, a magnitude 7.0 earthquake occurred in the Dodecanese sea (37.84°N, 26.81°E, 10 km depth), that generated a tsunami with an observed run-up of more than 1 meter on the Turkish coasts. Both the earthquake and the tsunami produced acoustic and gravity waves that propagated upward, triggering co-seismic and co-tsunamic ionospheric disturbances.

This paper presents a multi-instrumental study of the ionospheric impact of the earthquake and related tsunami based on ionosonde data, ground-based and Swarm-based GNSS receivers, and Jason3/DORIS [L1] receivers in the Mediterranean region.

Our study focuses on the Total Electron Content derived from the European GNSS network, Swarm, and Jason3, to describe the propagation of Medium Scale Travelling Ionospheric Disturbances (MSTIDs), possibly related to gravity waves triggered by the earthquake and tsunami. We use simultaneous vertical ionosonde soundings to study the interactions between the upper and lower atmosphere.

The results of this study provide a detailed picture of the Litosphere-Atmosphere-Ionosphere coupling in the scarcely investigated area that is the Mediterranean region.

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JA08b - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Investigating Mauna Loa (Hawaii) eruption of November-December 2022 from space: recent results from GOES-R, Sentinel-2, and Landsat 8/9 observations

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On 27 November 2022, an eruption started at the Mauna Loa (Hawaii; USA) volcano after about 38 years of quiescence. The eruption took place at the summit caldera; the day after, it migrated to the upper Northeast Rift Zone, where lava effusion initially occurred from three fissure vents. In this work, we investigate the Mauna Loa 2022 eruption, ending on 13 December, by means of a virtual network of multi-sensor infrared satellite observations. In particular, we show the results achieved by implementing the Normalized Hotspot Indices (NHI) on GOES-R ABI data, at 10 min temporal resolution, and by using Sentinel-2 MSI and Landsat-8/9 OLI/OLI-2 observations at mid-high spatial resolution via the Google Earth Engine tool developed to map volcanic thermal anomalies at global scale. Both the eruption onset and the short-term variations of thermal activity were well identified by NHI, using GOES-R ABI data. Moreover, an accurate mapping and characterization of active lava flows was performed. These results confirm that SWIR (short wave infrared) observations, at different temporal and spatial resolution, if properly analysed, may support the monitoring and surveillance of active volcanoes from space.

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JA08c - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Electromagnetic monitoring experiment of the Cumbre Vieja eruption (La Palma, Canary Islands)

DOI: 10.57757/IUGG23-1745 - [LINK]

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Volcanic eruptions are key scenarios for developing new tools for volcanic monitoring. Among the geophysical techniques, electromagnetic methods are not extensively used in volcano monitoring. However, these methods are very sensitive to temporal changes in the subsoil due to the movement of fluids, which strongly affects the electrical resistivity of the subsoil.

During the volcanic eruption that started on the island of La Palma on September 19th, 2021, and the subsequent post-eruptive process, we deployed several magnetotelluric (MT) stations in the vicinity of the new volcano to test the performances of such instrumentation as an effective volcanic monitoring tool. Magnetotelluric stations have been installed for continuous monitoring, recording electric and magnetic fields along the N-S and E-W directions. We have obtained good quality transfer functions for the period range of 0.01 - 100 s. The main objective of this MT experiment was to detect possible variations of the apparent resistivity and phase curves and to compare them with other geophysical and geochemical studies conducted in the same area.

The preliminary results show slight changes in the resistivity over time that could be related to the development of a shallow hydrothermal system around the volcano.

Furthermore, in comparing the pre-eruptive 3D resistivity model of the island, we observed that regions with low resistivity were almost aseismic, possibly due to the presence of ductile rocks like clays.

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JA08c - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Detecting Tonga volcanic-eruption effects on ionosphere, using satellite geodetic techniques

DOI: 10.57757/IUGG23-3483 - LINK

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The occurrence of some natural hazards in the troposphere may lead to creation of Internal Gravity Waves (IGWs). These waves transfer energy from the lower troposphere to upper layers, and to the ionosphere. When these IGWs reach the ionosphere, they create significant variations in the ionospheric parameters such as Total Electron Content (TEC) and electron density. Therefore, they have considerable effects on performance of Global Navigation Satellite Systems (GNSS) receivers.

In this study, we used double-frequency measurements of GNSS ground-based stations from GEONET network in New Zealand to detect the IGWs created by the tsunami induced from the 2022 Tonga volcanic eruption. In addition to GNSS measurements, radio occultation (RO) data from FORMOSAT-7/COSMIC-2 (F7/C2), and SWARM data were also used to study these IGWs.

It is known that IGWs and tsunami waves have similar characteristics such as horizontal speed, frequency, and arrival time. But as the volcanic-originated IGWs spread in cone-shape pattern, it is possible to detect them earlier than the tsunami waves, reaching the tide gauges or DART buoys. In our study, we could detect the first patterns of IGWs at the New Zealand GNSS stations, two hours earlier than the first tide gauges and DART buoys near the New Zealand peninsula, which is located approximately 1.600 km from the Tonga Volcano.

It can be concluded that IGWs can be used to warn tsunamis faster than the current early-warning systems, which make use of tide gauges and DART buoys.

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JA08c - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

VLF observation of the Low ionospheric shock wave produced by the Hunga-Tonga Volcano explosion

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The low ionosphere, height ~ 60-70 km, is highly sensitive to disturbances of extraterrestrial origin as quiet and disturbed solar electromagnetic emissions, as well as strong atmospheric and/or geological events. This is the case of the ionospheric disturbance observed on January 15, 2022 associated to the shock wave generated by the eruption of the Hunga-Tonga volcano. In this work, we present evidence of the propagation at lower ionospheric layers, specifically in the D region of the shock wave produced by this volcano explosion. Through simulations and a detailed analysis of the effects of the wave over the VLF path, between the NAA transmitter (USA) and the receiver station at Mexico City (CdMx), located at ~ 14 000 and ~ 10 000 km, respectively from the Hunga-Tonga volcano. We estimated that the shock wave propagated at ~ 880 m/s, which is faster than the propagation speed reported at higher ionospheric altitudes.

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JA08c - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Development of 3D ionospheric Tomography and its Application to Ionospheric Disturbances Related to Typhoon and the 2011 Tohoku-Oki Earthquake

DOI: 10.57757/IUGG23-3736 - LINK

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Conventionally, two-dimensional spatio-temporal variations and one-dimensional temporal variations such as GNSS-based TEC fluctuations and ionosonde data have been used for ionospheric disturbances. Ionospheric disturbances such as Pre-earthquake phenomena, and triggered by seismic ground motions, tsunamis, and typhoons, for which the physical mechanisms have not yet been elucidated, were also studied using GNSS-based TEC and Ionosonde data. In this study, we introduce the newly developed an ionospheric tomography system that is stable even during disturbances and can reconstruct the three-dimensional ionospheric electron density distribution. And we apply the developed tomography method to the GEONET data with typhoon signature and earthquake-related disturbances around Japan. Based on the obtained the three-dimensional structure, it is highly suggestive that ionospheric disturbances caused by typhoons were excited by atmospheric gravity waves, seismic fluctuations by sound waves, tsunami-induced fluctuations by atmospheric gravity waves, and earthquake precursors by electric fields. Details will be shown in the presentation.

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JA08c - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Tracking and Investigating Land Subsidence in Himalayan town using PSInSAR techniques: Lessons from Joshimath

DOI: 10.57757/IUGG23-4156 - LINK

Kirti Kumar Mahanta[1], *Ankit Singh*[1], *Sharad Kumar Gupta*[2], *Dericks Praise Shukla*[1]
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[2]*Tel Aviv University, School of Environment and Earth Sciences, Tel Aviv, Israel*

Joshimath is an Indian Himalayan town built on a paleo landslide and fragile mountain slope of a landslide-prone region. By the end of 2022, local people identified numerous cracks in the buildings and grounds of Joshimath. The local administration ordered to demolish the unsafe structures to minimize socioeconomic losses, resulting in conflict between people and the administration. The leading cause of these crack developments or land subsidence are the construction activity of NTPC's Tapovan-Vishnugad hydro project, rapid urbanization, and population overgrowth. However, the local geological conditions, including lithology and thrust zone, control the magnitude of land subsidence. Microwave Remote sensing, mainly the Persistent Scatterer Interferometry Synthetic Aperture Radar (PSInSAR) technique, has emerged as a promising tool for monitoring land subsidence with millimetre precision. Hence, in this study, we have used 32 Sentinel-1 SLC images acquired from January 2022 to January 2023 along ascending orbit to track land subsidence over the Joshimath area. The StaMPS algorithm processed the InSAR images by considering 0.4 as the amplitude dispersion threshold, 3 patches in range and 2 patches in azimuth. The results revealed a significant land displacement rate of -0.5mm/year to -65mm/year. High displacement rates are observed in various locations on debris of paleo landslide. Similar subsidence has been reported by local news channels at various other locations in Himalayas. Further, work can be carried out to estimate the rates of deformation at other locations as well, such as Shimla, Dharamshala, Theog, Kufri, Almora, Nainital, Mussoorie, and other mountainous regions around the globe.

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JA08c - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Comparing Landslide Susceptibility in Northwest and Northeast Himalaya: A Case Study of Kangra and Tamenglong Districts

DOI: 10.57757/IUGG23-4157 - LINK

Ankit Singh[1], Niraj kc[1], Nitesh Dhiman[1], Kirti Kumar Mahanta[1], Sharad Kumar Gupta[2], Dericks Praise Shukla[1]
[1]Indian Institute of Technology Mandi, School of Civil and Environmental Engineering, MANDI, India
[2]Tel Aviv University, School of Environment and Earth Sciences, Tel Aviv, Israel

The increasing effect of climate change and anthropogenic activities have left the mountains under great stress, resulting in Natural Hazards. Among all other natural hazards, landslide poses a significant threat to life and property. In recent decades, plenty of literature has been available on the application and methodology adopted in preparing landslide susceptibility maps (LSMs), mainly focusing on the Himalayan region. However, fewer attempts have been made to compare the susceptibility in North-Western and North-Eastern Himalaya. Hence, in this study, LSM is prepared for 2 districts; one district of northwest i.e Kangra, Himachal Pradesh and one district of northeast i.e. Tamenglong, Manipur. The landslide inventory was prepared using available data, field data and satellite image interpretation, and nine causative factors were used in LSM preparation using frequency ratio (FR). The results showed that in the Kangra district, the weight of lithology was highest followed by distance to road and lineament, while in Tamenglong, the importance of distance to road was highest. 16% area in Kangra and 31% in Tamenglong district falls in high and very high landslide suscpetibile area. In addtion, Tamenglong district had more significant portion of high and very high suscpetibile area compared to Kangra district. The AUC value of LSM for Kangra and Tamenglong district was 0.91 and 0.89, respectively. Generally, due to excessive precipitation, fragile geology, earthquake and tectnoic activities it is seen that, in northeast areas are more susceptible to landslide as compared to northwest Himalaya.

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JC06a - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Understanding the Downstream Dynamics of Mountain Cryosphere Hazards

DOI: 10.57757/IUGG23-3580 - LINK

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[3]*Institute of Engineering- Tribhuvan University, Department of Civil Engineering, Kathmandu, Nepal*
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Some of the most destructive mountain cryosphere hazards are those that generate far-traveled flows, most notably glacial lake outburst floods (GLOFs), but also mass wasting or glacial collapse triggered flows. These events can travel 10s to 100s of kilometers downstream through the fluvial network, and the processes that take place during this propagation may play a significant role in the magnitude and type of impact that such events have on both downstream communities and the fluvial system. While there has been substantial progress in our understanding of the past occurrence, potential sources and triggers, and initial stages of such events, particularly GLOFs, there are still a number of key open questions about their subsequent behavior. Understanding the interaction between propagating flows and the water, sediment, and channel properties they encounter as they propagate downstream is critical for the accurate estimation of the hazard potential of possible flow sources. These questions are highlighted by the complexity of several recent large events in the Himalaya, including the 2021 Chamoli event, the 2021 Melamchi flood, and the 2016 Bhote Koshi GLOF. Using new techniques such as environmental seismology, combined with advances in remote sensing and observer documentation, we can make progress towards understanding the evolution of such events as they propagate downstream.

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JC06a - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Susceptibility assessment for glacier hazards in the Rio Volcan basin, Central Andes of Chile

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The Chilean Central Andes have been under severe hydrological stress due to the uninterrupted megadrought for the last 13 years. The region is known for being the denser populated zone of the country and it hosts a wide variety of glaciers along with the largest ice masses outside Patagonia.

This work presents a susceptibility assessment for glacier hazards in the Rio Volcan basin (-32.82°/-70.00°), located 40 km east of Santiago city. The region is characterized for elevation ranges from 3380 to over 6000 m a.s.l. at the active and glacier-covered San José Volcanic Complex. Its closeness to the capital favours outdoor activities, tourism, urban and hydroelectric power development. Nowadays, there are accounted 195 glaciers in the area, including 46 glaciarets, 16 mountain glaciers and 8 valley glaciers.

The susceptibility of 5 different phenomena is evaluated based on an analytical hierarchic process method through the determination of a susceptibility index. The multiple processes evaluated include ice avalanches, surges, low-angle glacier detachments, GLOFs and eruption-triggered lahars.

The results show that within the Rio Volcan basin 4 glaciers are highly susceptible for ice avalanches, 1 for surges, 2 for sudden low-angle detachments, 3 for GLOFs whereas 19 glaciers, mainly glaciarets (68 %), are highly susceptible for eruption-triggered lahars. Only the 7 km-long Loma Larga glacier is highly susceptible for 4 out of 5 assessed processes excluding lahars.

It is concluded that the proposed method can be used in other regions after adjustments regarding the work scale and conditioning factor’s weight are applied.

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JC06a - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

High risks from hidden lakes - Glacial lake outburst floods in the Trans-Himalaya of Ladakh, India

DOI: 10.57757/IUGG23-4231 - LINK

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Cryosphere-related hazards are a growing but largely neglected threat for rural settlements, agrarian land use and local livelihoods in the cold-arid Trans-Himalaya. Despite the growing number of studies on cryosphere-related hazards, the occurrence, frequency and magnitude of glacial lake outburst floods (GLOFs) are almost entirely overlooked for the region of Ladakh. Due to the small size and high elevational location of glaciers above 5200 m a.s.l. also the glacial lakes are of small size. In the recent past several GLOF events occurred which destroyed infrastructure and agricultural area. It becomes obvious that even these small glacial lakes might be a permanent threat for local livelihoods and socioeconomic development. This is even more problematic as the number and size of lakes has significantly increased over the past decades. A comprehensive inventory of glacial lakes for the entire Trans-Himalayan region of Ladakh was carried out. This includes several almost permanently ice-covered high altitude lakes. Changes in the extent and number of glacial lakes have been quantified since 1969 in order to assess the potential threat of future GLOFs in the region. The lake development of selected former reported GLOF events and disappeared glacial lakes were analysed in detail to reconstruct lake level changes which possibly indicate earlier GLOF events. Based on high temporal resolution remote sensing data, a sophisticated monitoring concept needs to be realized to indicate the development of short-lived lakes on glaciers or on debris landforms with buried ice or fast glacial lake growth.

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Modelling the flow and impact of Glacial Lake Outburst Floods: Application to case studies in Pakistan and Bhutan

DOI: 10.57757/IUGG23-3620 - LINK

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Glacial Lake Outburst Floods (GLOFs) are a major hazard in high mountain areas, and can significantly impact transportation infrastructure, human settlements, water supplies, agricultural land, and important cultural and religious locations. Dynamic flow models are widely used for hazard assessment, preparedness planning and to support Early Warning Systems for other destructive sediment flows including flash floods and debris flows, and here we present results of their application and calibration for GLOFs. We use the LaharFlow model (www.laharflow.bristol.ac.uk), a dynamic sediment flow model for hazard assessment, which solves conservation equations for mass and momentum under the shallow layer approximation, to compute the flow dynamic properties. LaharFlow includes parameterizations for erosion and deposition, and the variation in flow solids concentration, friction and landscape change that result, and is freely-available as a webtool.

We applied the model to recent case studies that represent a range of GLOF sizes: at Ghulkin (Pakistan, 2022), Shisper (Pakistan, 2020) and Lemthang Tsho (Bhutan, 2015), and also to potential future impacts on Paro (Bhutan). Source conditions were constrained using estimates of lake volumes and idealised hydrographs corresponding to an instantaneous moraine wall failure and slow drainage. The modelling shows good agreement for observed flow depths, speeds, erosion patterns and arrival times using parameters calibrated for other large debris flow settings. For the Paro example, we show how dynamic models can be used to identify locations for, and calibrate, early warning systems, and to assess potential impacts of GLOFs on communities living in high mountain environments.

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JC06a - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Mapping release and propagation areas of permafrost-related rock slope failures to identify hot spots for hazard assessment, French Alps

DOI: 10.57757/IUGG23-1859 - LINK

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Permafrost-affected rockwalls are increasingly impacted by the effects of climate change and rising air temperature leading to rock slope failures. These events could be a threat for human lives and infrastructure, which underlines the need of better knowledge about their triggering mechanism and propagation. The aim of this study was to propose a regional mapping approach of susceptible release areas of rock slope failures and resulting runout distances. This information is a first step to identify hotspots for subsequent hazard assessment.

To do so, we used an inventory of 1389 rock slope failures (volume > 10^2 m^3) recorded in the Mont-Blanc massif on 2007-2019 period and determined the topographical and permafrost conditions that are most prone to their triggering using a digital terrain model and a permafrost map. These conditions are used in a multi-criteria GIS approach to identify potential unstable slopes at the French Alps scale. Then, the potential release area map is used as input to map the propagation of potential events, using a model based on a normalised area dependant energy line principle. The resulting maps of release and propagation areas will be used to point out human assets (mountaineering routes, high mountain infrastructure, tourism areas) and lakes (that can provoke cascading hazards) which could be impacted by rock slope failure hazards.

This work is a first step to identify hot spots for a regional hazard assessment where more in depth analyses will be required to evaluate potential risks at a local scale.

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JC06b - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

How can seismology provide a better understanding of mountain cryosphere hazards?

DOI: 10.57757/IUGG23-2456 - LINK

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[2]Géoazur, Observatoire de la Côte d'Azur- CNRS- IRD- Université Côte d'Azur, Sophia Antipolis, France
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[5]Geotest AG, Geotest AG, Zollikofen, Switzerland
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Glacier and slope instabilities pose significant hazards in mountain areas, with a high potential impact on the population. Forecasting glacier and slope instabilities remains challenging as sensing technology focusing on the surface might fail to detect damage and changes in subsurface elastic properties leading to large-scale failures. Seismic methods, such as seismic interferometry, can help address this observational gap by quantifying changes in material integrity. Here, we discuss two case studies in which seismology elucidates the development of cryospheric hazards: a hanging glacier instability and permafrost degradation on an active rockslide.

We first analyze seismic data from Switzerland's Eiger hanging glacier before a 15,000 m^3 break-off event. Our approach, based on an analysis of multiple icequake waveforms, allows us to measure seismic source migration. Combined with an analytical model based on damage mechanics our results quantify crevasse extension between unstable and stable ice masses. We then move to the second study site, an active rock slope near "Spitze Stei" in the Kandersteg region, Switzerland. The time series of relative seismic velocity variations (dv/v) constrain the lateral and depth-dependent extent of changes in the rock's elastic properties caused by pore pressure increase and potentially by permafrost thawing.

The presented case studies illustrate how seismology can give quantitative insights into material damage and allow separating effects of irreversible damage growth from reversible thermoelastic hydrologic variations. This knowledge is needed to better predict the development of large failures and thus improve warning systems.

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JC06b - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Climate-change-induced seismicity: The recent onset of seasonal microseismicity at the Grandes Jorasses, Mt. Blanc Massif, France

DOI: 10.57757/IUGG23-4234 - LINK

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Modeling studies suggest that climate change may cause a dynamic response of the geosphere, increasing geological and geomorphological hazards. These hazards include a potential rise in earthquake activity driven by climate-change-induced changes in the hydrological subsurface conditions. So far, evidence for this phenomenon is rare and often inconclusive.

Here, we investigate an ongoing earthquake swarm with thousands of shallow ML<3 events in the Mount Blanc Massif that shows an annual periodicity starting in fall 2015. Comparing its activity with runoff volumes and isotope data from the Mont Blanc tunnel indicates that the seismicity is driven by snow and glacier meltwaters. Since 2015, near-surface flow paths rearranged by permafrost and glacier retreat may have allowed these waters to reach the source region.

Our QuakeMatch-analysis (Toledo et al., 2023) combines matched-filter detection sensitivity and consistent magnitude estimation with high-precision relocation and statistical analysis. It reveals that the seasonal component of the seismicity shows high b-values supporting the meltwater-driven origin, while the non-seasonal component shows a tectonic b-value around 1.0 dominated by earthquake-earthquake interaction. The seismicity increase since 2015 is associated with an increase in the short-term seismic hazard (STSH). In the high-activity phases, the STSH increased by up to two orders of magnitude compared to the STSH level before 2015.

The meltwater-driven seasonality and the associated increase in STSH provide observational evidence that climate change can increase seismic hazard locally. Similar phenomena may be ongoing in glaciated regions worldwide. Our study can contribute to better quantifying the seismic risk for affected alpine communities.

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JC06b - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Avalanche detection using existing telecommunication infrastructure and Distributed Acoustic Sensing

DOI: 10.57757/IUGG23-4714 - LINK

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We demonstrate the detectability of snow avalanches using Distributed Acoustic Sensing (DAS) with existing fiber-optic telecommunication cables. To achieve this, during winter 2021/2022, we interrogated a ~10 km long dark fiber that follows the avalanche-prone Flüelapass road in the Swiss Alps. In addition to other signals like traffic and earthquakes, the DAS data contain clear recordings of numerous snow avalanches, even though many of them did not reach the sensing cable itself, as revealed with automatic cameras and images taken by drone. The spatial resolution of the detection is of the order of few tens of meters. Avalanche signals can produce strong strain fluctuations exceeding 3 µm/m/s and they exhibit specific characteristics in terms of frequency content and apparent velocities which, we believe, can be used to discriminate them from other types of events. Our results open new perspectives for cost-effective, near-real-time avalanche monitoring over long distances using pre-installed fiber-optic infrastructure.

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JC06b - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Avalanche occurrences in Norway deduced from meteorological data

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Avalanche formation depends on terrain characteristics, snowpack, and meteorological conditions. Of these, meteorological parameters, such as temperature, precipitation, and wind, strongly influence the possibility of a catastrophe in an avalanche-prone area. One-fourth of Norway´s public roads are exposed to the risk of avalanches; hence, the Norwegian Meteorological Institute (MET Norway) produces daily warnings on a scale of 1-5, 5 being the maximum danger level of risk of avalanche activity. The warnings are restricted to the winter period, i.e. December, January, February, March, and April. In this study, we identify the regions in Norway with high avalanche warnings (warning >= 4, named the `avalanche day´) based on the MET warnings. Four regions in Norway, namely Ofoten, Salten, Svartisen, and Hegeland, observed maximum avalanches (>= 35) between Dec 2017 and April 2022.

The two conditions that drive the instability of the snowpack are (i) loose snow and (ii) slab avalanches. In particular, wet snow instances and persistent weak layers in the snowpack of slab avalanches are responsible for most avalanches in these four regions. To understand the impact of meteorological variables on these avalanches, we utilise the long-term observational gridded datasets (1 km resolution) from MET Norway. Over the last five years (Dec 2017- April 2022), during the winter months, the daily mean temperature analysis shows an increase three days before the `avalanche day´, but the accumulated precipitation increases by 12.5% a day before the event. Future work entails analysing long-term climate data for avalanche monitoring and prediction studies.

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JC06b - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

What causes the recent jökulhlaup drainage perturbations in Zackenberg, NE-Greenland?

DOI: 10.57757/IUGG23-4351 - [LINK]

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[7]Undo, Enhanced Weathering Monitoring, Darlington, United Kingdom

Since 2005 quasi-annual jökulhlaups, or glacial lake outburst floods, are registered at the Zackenberg research station (74°28′N, 20°34′W), NE-Greenland. The jökulhlaups typically happen during the sommer months, but were also observed during winter and spring. The Zackenberg jökulhlaups exhibit rapid-rising outburst type characteristics with durations of 12-24 hours, and maximum discharges of 120 to 380 m^3/s. The source is a lake dammed by an outlet glacier of the A.P. Olsen ice cap about 35 km inland of the research station. The recorded maximum ice-dammed lake volumes are varying in between 5.7 to 15.6 $x10^6$ m^3.The year 2018 showed no drainage event and the lake remained filled until the 2019 melting season, accumulating the largest lake volume so far. The 2019 lake outburst happened with beginning of July rather early, but just drained slowly for more than a week to then switch to a rapid-type outburst emptying the lake in about half a day. The subsequent 2020 and 2021 floods continued to show characteristics of slower and mixed-type drainage events. The overall evolution of the 2019-2021 lake drainage patterns suggest a transition back to rapid-type jökulhlaup events. To our knowledge, the observed mixed-type drainage patterns within a single jökulhlaup event has been never reported before, and is challenging the current understanding of subglacial floods. We present all the available hydrometric data for the Zackenberg river and the ice-dammed lake to discuss potential causes for the observed jökulhlaup perturbations.

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JG01a - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

GNSS Measurements of GIA-driven crustal deformation in Antarctica

DOI: 10.57757/IUGG23-2206 - LINK

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Continuously recording GPS stations have operated at permanent Antarctic research stations, mainly along the coast, for nearly 3 decades. In contrast, deployment of continuously recording autonomous GPS instruments in the continental interior of Antarctica started mainly during the 2007-08 International Polar Year. At present, the U.S. ANET-POLENET and UK-ANET projects maintain most GNSS stations across interior and remote coastal West Antarctica and the Antarctic Peninsula; these projects have limited-term support and are currently scheduled to end within the next 2 years. Cessation of data acquisition, due to lack of operational support and/or site decommissioning, is resulting in a crucial gap in observational constraints for GIA modeling. It also hinders a range of studies using GNSS data, spanning the deep Earth to the ionosphere.

Geodetic time series from autonomous GNSS systems distributed across Antarctica have revealed unexpected patterns and startling rates of crustal deformation due to GIA. Linked with seismic mapping and derived rheological properties of the Antarctic crust and mantle, and with new advances in GIA modeling capabilities, GNSS observations have transformed our understanding of the timescales of GIA response to ice sheet change. Rapid GIA response promotes cryosphere-solid earth interactions that can alter ice sheet behavior on decadal and centennial timescales, with significant implications for the contributions of marine-based sectors of the Antarctic Ice Sheet to sea level in the future. Continued progress in understanding how such feedbacks should be adopted in global sea level projections requires continuing and expanding our geodetic observations through international cooperation.

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JG01a - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Spatially resolved GIA in Antarctica from a global inversion

DOI: 10.57757/IUGG23-2570 - LINK

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[4]TU Delft, Faculty of Civil Engineering and Geosciences, Delft, Netherlands

The mass balance of the Antarctic Ice Sheet (AIS) can be obtained from time-variable gravity fields from GRACE and GRACE-FO. This is useful to investigate the ice sheet's adaption to a changing climate and its contribution to the global mean sea level. However, the correction for the present-day glacial isostatic adjustment (GIA) in Antarctica is still the largest uncertainty contributor in gravimetric mass balances. Lacks of knowledge of the ice loading history and the solid Earth's rheology lead to a large spread of GIA predictions from forward modelling approaches. We developed a method (Willen et al. 2022, https://doi.org/10.1007/s00190-022-01651-8) that allows to spatially resolve GIA, ice mass changes, and firn thickness changes in Antarctica within a globally consistent framework using geodetic satellite data and results of climate modelling. From simulation experiments, we found that the signal separation is possible despite data limitations as long as accounting for spatial error covariances of the input data sets. Here, we present and discuss results from a global inversion of satellite gravimetry data (from GRACE/GRACE-FO), satellite altimetry data (CryoSat-2), regional climate modelling (from RACMO2), and modelled firn thickness changes (from IMAU-FDM) over the time period Nov 2010 to Dec 2020. Furthermore, we will discuss the advantage of implementing this methodology in a global sea level inversion framework.

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JG01a - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Reprocessing of geodetic GNSS recordings in Antarctica for geodetic and geodynamic applications (GIANT-REGAIN)

DOI: 10.57757/IUGG23-3431 - LINK

Mirko Scheinert[1], Eric Buchta[1], Matt King[2], Terry Wilson[3], Demian Gomez[3], Eric Kendrick[3], Achraf Koulali[4], Peter Clarke[4], Christoph Knöfel[1]
[1]TU Dresden, Geodetic Earth System Research, Dresden, Germany
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Changing ice masses cause deformation of the solid Earth on different time scales. The classic view discriminates between elastic deformation and glacial-isostatic adjustment (GIA) due to present-day and past changes, respectively. The increasing availability of observational data and modelling advances allows our understanding of the complex pattern of solid Earth response to improve, including observation of rapid GIA.

Geodetic GNSS provides a technique to directly observe bedrock motion. In Antarctica, several studies already utilized such GNSS data but were limited in time or to a specific region, or could use recordings of only a limited number of stations. Within the SCAR-endorsed project GIANT-REGAIN a reprocessing of all available Antarctic GNSS data was realized, comprising data acquired by episodic and permanent recordings at about 280 bedrock sites between 1995 and 2021. Special attention was given to metadata which are indispensable for a correct assignment of the hardware set-up. The four processing centres applied precise point positioning or differential GNSS using different scientific software. Time series of consistent point coordinates were generated as the major product.

We will report on the comparison of the different solutions which allows to quantify time series analysis uncertainty. From the time series, coordinate velocities will be estimated. Here, we will discuss different aspects such as useful noise models, spatial correlations and suitable trajectory models. The treatment of the solid Earth response to ice-mass changes occurring over the last decades up to present day is currently under strong discussion and will be touched briefly.

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JG01a - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Geodetic GNSS observations disclose the response of the solid Earth to changing ice masses in Dronning Maud Land, East Antarctica

DOI: 10.57757/IUGG23-3435 - LINK

Eric Buchta[1], Mirko Scheinert[1], Matthias Willen[1], Maria Kappelsberger[1], Lutz Eberlein[1], Benjamin Schröter[1], Christoph Knöfel[1], Martin Horwath[1]
[1]TU Dresden, Geodetic Earth System Research, Dresden, Germany

Geodetic GNSS measurements on bedrock allow to determine secular trends of solid Earth deformation and, therefore, provide valuable constraints for modelling glacial-isostatic adjustment (GIA). There is a high discrepancy in GIA model predictions of vertical displacement rates in Antarctica regarding their spatial pattern and magnitude. While in West Antarctica, in the Antarctic Peninsula and in parts of Victoria Land a comparably large number of GNSS stations exists, East Antarctica exhibits big gaps in the GNSS coverage. The sparsity of bedrock outcrops and the difficult accessibility and logistics are reasons for this.In order to improve the spatial coverage we established a GNSS network in western and central Dronning Maud Land, East Antarctica, with first observations carried out already in the mid-1990ies and a latest observation campaign realized in the Antarctic season 2022/2023. Here we present results of a consistent processing of all episodic and permanent GNSS measurements in that region. We discuss how the long time basis of more than 20 years helps to improve the accuracy of the secular trend inferred from the GNSS time series. We remove the elastic deformation due to present-day ice-mass changes utilizing satellite altimetry observations and surface mass balance models. We discuss our resulting trends in comparison to existing GIA models in a region sparsely covered by GNSS prior to this study.

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JG01a - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Mapping geodetically inferred Antarctic ice height changes into thickness variations: A sensitivity study

DOI: 10.57757/IUGG23-4536 - LINK

Natasha Valencic[1], Linda Pan[1], Konstantin Latychev[1], Jerry Mitrovica[1]
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Determining recent ice volume changes from satellite measurements of ice height requires an estimate of contemporaneous vertical crustal deformation. This estimate must consider two main sources of crustal deformation: (1) ongoing glacial isostatic adjustment (GIA), that is, the deformational, gravitational and rotational response to late Pleistocene and Holocene ice and ocean mass changes; and (2) modern ice mass flux. The former has generally involved the adoption of global models of GIA defined by some preferred combination of ice history and mantle viscoelastic structure, while the latter has commonly been based on a simple, spatially invariant scaling of measurements of ice height. In the case of the Antarctic Ice Sheet, a scaling by ~1.02 has typically been adopted. We quantify the uncertainty and potential bias introduced in past estimates of the GIA signal using forward modeling results of various complexity. We also use modeling results to emphasize the spatially variable structure of the mapping between ice height changes and vertical crustal deformation associated with modern ice mass flux.

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JG01b - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

The deepest geoid low on Earth and its possible relation to the instability of the West Antarctic Ice Sheet

DOI: 10.57757/IUGG23-0176 - [LINK]

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[3]Evangelisches Gymnasium Hermannswerder, 10. Klasse, Potsdam, Germany

The deepest geoid low globally w.r.t. hydrostatic equilibrium is in the Ross Sea area. Nearby in West Antarctica is a residual topography high. Both are in a region with thin lithosphere, where a mantle plume has been suggested. Hence upper mantle viscosity could be regionally reduced, allowing for faster rebound than elsewhere upon melting of the West Antarctic Ice Sheet, one of the global climate system's tipping elements. To study possible causes of the geoid low / topography high combination, we compute the effects of disk-shaped density anomalies. With -1% density anomaly, geoid low and topography high can be explained with disk radius ~10° and depth range ~150-650km. Alternatively, there may be two separate disks somewhat laterally displaced, one just below the lithosphere and mainly causing a dynamic topography high and one below the transition zone causing the geoid low. In order to test the feasibility of such density models, we perform computations of a plume that enters at the base of a cartesian box corresponding to a region in the upper mantle, as well as some whole-mantle plume models, with ASPECT. However, these plume models have typically a narrow conduit and the plume tends to only become wider as it spreads beneath the lithosphere, typically shallower than ~300km, hence they would tend to rather under-predict the amplitude of the geoid compared to dynamic topography. We discuss how to possibly overcome the discrepancy between what is required to explain geoid and dynamic topography, and the outcome of numerical forward models.

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JG01b - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

On the path dependence of marine ice-sheet contribution to sea-level change

DOI: 10.57757/IUGG23-0356 - LINK

Surendra Adhikari[1], Lambert Caron[1], Eric Larour[1], Erik Ivins[1]
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The melting of ice sheets directly contributes to ocean mass and volume change. One key metric to keep track of ice-ocean mass exchange is the "ice-sheet contribution to sea-level change" (IS2SL), which is presumed to be a conservative metric that does not depend on what path an ice sheet takes to reach from its initial to final geometry. Conventionally, IS2SL is calculated by quantifying the change in ice volume above flotation. What appears to be a trivial book-keeping task unfolds a layer of complexities while quantifying IS2SL in real-world scenarios where ice sheets, solid Earth, and ocean geometries evolve continuously. Two research groups have independently proposed supposedly general formalisms to quantify IS2SL [1,2]. The two methods do not seem to agree, especially where an ice sheet transits from the grounded to the floating state, or the reverse, much of what happens in marine sectors of Antarctica or the former Laurentide Ice Sheet. In particular, one method appears to predict a path-dependent solution for IS2SL [1], challenging the utility of one of the most fundamental glaciological metrics. Here, with a simple kinematic analysis, we argue why IS2SL is inherently a path-dependent metric and caution the paleo- and modern glaciology communities regarding its utility for data and model intercomparisons.

[1] https://doi.org/10.5194/tc-14-2819-2020
[2] https://doi.org/10.5194/tc-14-833-2020

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JG01b - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

FastIsostasy.jl - Accelerated computation of glacial isostatic adjustment

DOI: 10.57757/IUGG23-0500 - LINK

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Glacial isostatic adjustment (GIA) represents an important negative feedback on ice-sheet dynamics. The magnitude and time scale of GIA primarily depend on the upper mantle viscosity and the lithosphere thickness. These parameters have been found to vary strongly over the Antarctic continent, showing ranges of 10^18 - 10^23 Pa s for the viscosity and 30 - 250 km for the lithospheric thickness. Recent studies show that capturing these spatial dependencies are of significant importance for the long-term evolution of the Antarctic Ice Sheet (AIS). However, 3D GIA models are computationally expensive and sometimes require an iterative coupling for the ice sheet and the solid-Earth solutions to converge. As a consequence, their use remains limited, potentially leading to errors in the simulated ice-sheet response and associated sea-level rise projections. Here, we propose to tackle this problem by generalising the work of Bueler et al. (2007) and Coulon et al. (2021). FastIsostasy allows for an explicit accounting of the effects of spatially heterogeneous viscosity and lithospheric thicknesses and is computationally very efficient.

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JG01b - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

The inevitable emergence of anelasticity in climate driven surface load response

DOI: 10.57757/IUGG23-2057 - LINK

Erik Ivins[1], *Lambert Caron*[1], *Surendra Adhikari*[1], *Eric Larour*[1]
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A general assumption in geodesy is that solid Earth deformation in the presence of recent hydrological and ice loading is well approximated by a purely elastic response. If thermal or petrological conditions exist that favor vigorous high-the temperature creep behavior, such as in the mantle beneath Iceland, Patagonia, Alaska, Japan and Svalbard, many response models have been approximated by using a Maxwell viscoelasticity. However, non-Maxwellian transient viscoelastic rheology is required for models of post-seismic relaxation. Here we reconsider the solid Earth response in light of a temperature-dependent transient viscoelasticity currently favored in the mineral physics and seismological communities.

We develop a mantle response Green's function that accounts for the vertical isostatic motion of the mantle caused by acceleration of ice mass loss for Greenland and Patagonia measured by remote sensing since 1992 and 1945, respectively. The Green's function may be used to examine how anelasticity may express itself in the uplift associated with accelerated surface ice and water loss. We perform an extensive parameter exploration of the constants that define the Extended Burgers Material (EBM) model, a rheology having firm experimental and theoretical underpinnings, in order to isolate those material model parameters that have the greatest impact on anelastic-isostatic uplift over interannual and interdecadal time scales. Especially important are the contrasts among elastic, Maxwell and EBM predictions. Implications for the corrections for solid Earth vertical uplift in space gravimetric solutions for long-term hydrology and cryospheric change are also discussed.

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JG01b - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Glacial Isostatic Adjustment and sea-level change in Singapore and Southeast Asia: Implications from past to future

DOI: 10.57757/IUGG23-0540 - LINK

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[4]*University of Calgary, Department of Geoscience, Singapore, Singapore*

Over 400 million people in Southeast Asia live in low elevation coastal zones and are susceptible to future relative sea-level (RSL) rise. Projections of future RSL rely on an accurate understanding of sea-level driving processes such as Glacial Isostatic Adjustment (GIA). Here we apply GIA models, paleo RSL records and instrumental data to demonstrate the evolution of RSL changes in Singapore and Southeast Asia and the associated impacts.

We reconstructed RSL since the Last Glacial Maximum (LGM) to quantify magnitudes and rates of RSL changes through time and used GIA model to assess paleotopography changes and impacts to human populations. We applied the Intergovernmental Panel on Climate Change (IPCC) RSL projections and used the geological past to provide probability perspectives when IPCC future projections were last exceeded in Singapore. Future projections under a moderate emissions scenario show RSL rising 0.95 m at a rate of 7.3 mm/yr by 2150 which was only exceeded (> 99% probability) during rapid ice melting events (MWPs) ~14.5 and ~9 ka BP. We inferred the human population history using 763 high-coverage whole-genome datasets. Integrated paleotopographic and population genomic analysis demonstrates the earliest documented instance of forced human migration driven by rapid sea-level rise (e.g., WMPs). We investigated the mid-Holocene highstand sensitivity revealing that Earth model variation affects the magnitude and ice model variation changes both the timing and magnitude of the highstand. Lastly, we produced a highstand “treasure map” to guide future highstand data collection efforts as the highstand is poorly constrained currently.

Over 400 million people in Southeast Asia live in low elevation coastal zones and are susceptible to future relative sea-level (RSL) rise. Projections of future RSL rely on an accurate understanding of sea-level driving processes such as Glacial Isostatic Adjustment (GIA). Here we apply GIA models, paleo RSL records and instrumental data to demonstrate the evolution of RSL changes in Singapore and Southeast Asia and the associated impacts.

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JG01c - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Can glacial isostatic adjustment modelling confirm potential signs of glacially triggered faulting in Canada?

DOI: 10.57757/IUGG23-1736 - LINK

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Glacial isostatic adjustment (GIA) leads to remarkable stress changes in the subsurface which can be potentially released along favourably orientated pre-existing fault structures, a process nowadays termed glacially triggered faulting. A notable vertical shift of some meters can occur. In coastal areas this can affect the measured elevation of relative sea level markers. In such case these markers must be corrected before they can be used in palaeo-sea level investigations.

Compared to Fennoscandia, the vast area of Canada does, so far, not contain any prominent traces of glacially triggered faulting which has led to interesting speculations in the literature. We will briefly review any suggested glacially induced faults in Canada and then analyze GIA-induced stress changes from a 3D finite element model of North America. We thereby test different stress regimes and (hypothetical) fault configurations to identify the most plausible fault parameters for reactivation. We will highlight the best parameter combinations for each fault or location of concern and compare them to available field observations. We will show that glacially triggered faulting has very likely affected most parts of Canada, including intraplate areas and Arctic islands. One example suggests that some relative sea level markers should be carefully used because faulting may have shifted the sample to a new elevation.

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JG01c - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

High-resolution modeling of dynamic vertical land movement in the Northern Hemisphere due to changing ice sheets and glaciers

DOI: 10.57757/IUGG23-0644 - LINK

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The impact of elastic vertical land movement (VLM) on relative sea levels along the world's coastlines is significant. In Northern Europe, VLM is mainly due to the effect of Glacial Isostatic Adjustment (GIA). However, the rapid melting of ice in the Arctic is causing a substantial elastic uplift with both a local, but also a long-range footprint of 1000-3000 km from the point of ice loss. When VLM estimates from GNSS are unavailable, sea-level studies based on tide gauges often rely on a GIA-only VLM model to correct any ongoing uplift, but in Arctic regions, this can lead to underestimation of the uplift or overestimation of the absolute sea-level change due to significant changes in present-day ice loading (PDIL).

Here, a high-resolution time-varying elastic VLM model (5x5 km) is developed from high-resolution estimates of glacial and Greenland Ice Sheet mass balance is presented. The elastic VLM model is combined with a GIA model to create a complete VLM model that is comparable with GNSS-measured VLM rates (in a center of mass frame). Additionally, far-field elastic effects from the Antarctic and Terrestrial Water Storage are included to create a complete vertical deformation map for the Northern Hemisphere, that can complement sea level studies in areas with few or no GNSS measurements.

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JG01c - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Is transient creep necessary to explain sea level and crustal uplift data from Greenland?

DOI: 10.57757/IUGG23-3633 - LINK

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In the 1980s, a series of articles explored the potential importance of transient rheology in the glacial isostatic adjustment (GIA) process (e.g., Peltier et al., *Geophys. Res. Lett.*, 1980; Sabadini et al., *Geophys. Res. Lett*., 1985; Yuen et al., *J. Geophys. Res*., 1986). However, in the absence of observational evidence for a time dependent viscous response, this level of additional modeling complexity fell out of favor in the GIA community. Recently, a comparison of viscosity models inferred from Holocene relative sea level data and modern crustal uplift rates in Greenland – the latter suggestive of a significantly lower Maxwell viscosity than the former – has renewed interest in the intriguing possibility of transient mantle creep (Adhikari et al., *Earth Planet. Sci. Lett.*, 2021). However, an unambiguous argument that transient rheology is necessary must rule out the possibility that a class of (Maxwell) viscosity models with general depth and lateral variability may reconcile both data sets. We present numerically derived 1-D sensitivity kernels for the relative sea level and uplift rate observations that demonstrate that these two data sets have independent sensitivities to variations in depth-dependent mantle viscosity. Moreover, we explore – within a broad class of such 1-D models – the level of fit that can be achieved to these data using a multi-layer Maxwell viscosity profile. Future work on this important, outstanding issue should extend this analysis of uniqueness using 3-D sensitivity kernels derived via adjoint methods (Crawford et al., *Geophys. J. Int.*, 2018).

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JG01c - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Improved Greenland glacial isostatic adjustment models with 3D Earth structure inferred from the joint inversion of regional data sets

DOI: 10.57757/IUGG23-3635 - [LINK]

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Changes in sea level and vertical land motion associated with glacial isostatic adjustment (GIA) are embedded in paleo and geodetic data sets used to constrain the past and future evolution of the Greenland ice sheet. Thus, understanding of ice sheet evolution goes hand in hand with our ability to simulate the GIA signal accurately. We aim to improve the accuracy of Greenland GIA simulations by interrogating regional geophysical data sets to determine better 3-D models of Earth structure in this region. We use a self-consistent Bayesian joint inversion framework (LitMod) to constrain lithosphere and shallow mantle properties and their uncertainty from multiple data sets. The inversion results indicate a high sensitivity to the input seismic dataset, so we incorporate a new, regional high-resolution surface wave dataset based on the two-station interferometry method. In terms of simulating GIA, a key inversion output is the regional temperature field. We sub-sample a high variance set of 25 temperature fields to define 25 models of the lithospheric thickness (LT) and 50 models of sub-lithosphere viscosity structure (using two different scalings). Our results indicate that viscosity and LT vary, respectively, by 3-4 and 2 orders of magnitude across Greenland. So the predicted GIA signal shows significant differences compared to simulations based on the more traditional 1-D (spherically symmetric) viscosity models. We will present results based on these 50 Earth models and two different ice history models and compare them to geological reconstructions of relative sea-level change and GNSS observations of vertical land motion.

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JG01c - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

The Influence of Topography and Sediment Cover Change on Pleistocene Glacial Cycles and the MPT with Coupled Ice Sheet-Climate-Sediment Physics

DOI: 10.57757/IUGG23-5010 - LINK

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A change from a low to high friction bed under the North American Ice Complex through the removal of pre-glacial regolith has been hypothesized to play a critical role in the mid-Pleistocene transition from 41 to 100 kyr glaciations. However, this regolith hypothesis requires constraint on pre-glacial regolith cover and topography, mechanistic constraints on what amount of regolith can be removed, and complete process coupling to infer the net effect from topography and sediment changes. This landscape evolution has not yet been simulated for a realistic, 3D North American ice sheet fully considering basal processes (e.g. sedimentary, basal hydrology, and the solid earth response to changing sediment and bedrock load). Constraints of the pre-glacial bed are sparse and the bounds are wide.

What constraint does the present day sediment distribution offer and how do topography and sediment change influence glacial cycles? Using varied pre-glacial topographies, sediment thicknesses, and fully coupled climate, ice, sediment and subglacial hydrology model parameterizations, we show the constraint on mean pre-glaciation sediment thickness provided by the present day surface sediment distribution and regional estimates of bedrock erosion. More broadly, we find that this landscape evolution has a strong influence on the strength and duration of early Pleistocene glaciations. The ice, climate, and sediment processes encapsulated in this fully coupled Earth systems model capture the evolution of the Pleistocene North American glacial system: the 41 to 100 kyr glacial cycles transition, early Pleistocene extent, sea level change, last deglacial margins, and broad present-day sediment distribution within uncertainty.

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JG01c - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Space geodetic data and validation method for global and regional glacial isostatic adjustment model optimization

DOI: 10.57757/IUGG23-2776 - LINK

Meike Bagge[1], Eva Börgens[1], Kyriakos Balidakis[1], Torsten Albrecht[2], Volker Klemann[1], Henryk Dobslaw[1], Bernhard Steinberger[1], Carina Haeger[1]
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Space geodetic data contain a glacial isostatic adjustment (GIA) signal, which is most prominent in formerly glaciated areas with present-day crustal uplift rates exceeding 10 mm/year in NE Canada and Central Sweden. Employing GNSS, VLBI, DORIS, and SLR data ingested into the latest international terrestrial reference frame (ITRF2020) we create a global dataset of GIA present-day uplift rates. We employ a multi-analysis-centre ensemble of GNSS station and geocentre motion coordinate solutions. Tectonic and weather signatures were reduced in estimating GNSS-derived velocities, and the trend signal is extracted from these GNSS time series with the STL method (seasonal-trend decomposition based on Loess). In addition, we develop a validation method for GIA model – data comparisons. As the geodetic stations are unevenly distributed, we employ a weighting scheme that involves network density and cross-correlation of the stations' displacement time series. As measures of agreement for global and regional cases, we employ the weighted root mean square error (RMSE) and the weighted mean absolute error (MAE). We apply the validation method to a large suite of GIA model simulations capturing uncoupled and coupled Solid Earth – Ice Sheet models, as well as laterally homogeneous and heterogeneous viscosity structures of the Earth's mantle, which are derived from a broad spectrum of geophysical data. The results suggest constraints on global and regional GIA model parameterisations in view of the considered observational data.

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JG07a - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Experimentation of new technologies for volcano gravimetry at Mt. Etna

DOI: 10.57757/IUGG23-2116 - LINK

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Among the geophysical techniques used to monitor volcanic unrest, only gravimetry can supply direct information on changes in the distribution of underground mass over time and can thus provide unique insight into processes such as magma accumulation in void space or gas segregation at shallow depths. Despite its great potential, time-variable volcano gravimetry is not widely adopted, mainly due to the high cost of instrumentation and the difficulty in assessing the relatively small volcano-related gravity changes against unfavorable environmental conditions.
Several past studies from Mt. Etna have highlighted the value of gravity observation for improving our understanding of how volcanoes work and characterizing volcanic hazards. In the early stages of application at Mt. Etna, time-lapse and continuous gravity measurements were accomplished using spring gravimeters. Successively, gravimeters based on different technologies have been employed, including superconducting and quantum devices. In most cases, these applications were world firsts at an active volcano.
Here, results from different gravimeter types, that have been used to monitor and study Mt. Etna, are presented. Furthermore, the perspectives opened by emerging technologies are highlighted.

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JG07a - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Gravity field of Lake Nasser, Egypt deduced from marine gravity survey and satellite altimeter data

DOI: 10.57757/IUGG23-1812 - LINK

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Lake Nasser, which was formed as a result of the construction of the High Dam, located in southern Egypt and Northern Sudan with a length of 500 km and a storage capacity of about 133.8 km 3. The seismic activity recorded in this region clearly indicates its connection with a tectonic pattern in the earth's crust, in addition to the change in the water level in the lake according to its annual water cycle for charging and unloading, which leads to breaking the equilibrium state in the lake by changing the weight of the lake resulting from the change in the water level and sediments accompanying it. Thus, the process of monitoring and evaluating alluvial sediments along the lake is of great importance because of its impact on the storage capacity of the lake as well as the navigational path of the lake in addition to the economic importance of these sediments. The availability of accurate gravitational data for Lake Nasser greatly contributes to determining the subsurface geological structures and stratigraphic sequences (depth of the base rocks and the thickness of the alluvial deposits at the bottom of the lake).

On the current research, high resolution marine gravity survey has been conducted along the main course of the Lake. Moreover, satellite altimeter data has opened new perspectives on determining the gravity field on the marine region. Therefore, satellite altimeter data has been utilized as integration with the marine gravity survey to evaluate the whole gravity field of the Lake.

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JG07a - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Evaluation of the AQG-B10 absolute quantum gravimeter for field measurements

DOI: 10.57757/IUGG23-3825 - LINK

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Falling corner cube gravimeters (FCCG) pose the current state-of-the-art instruments for absolute terrestrial gravimetry. However, already in the early 1990s, experimental quantum gravimeters have been demonstrated: a fundamentally different principle for measuring gravity based on probing the free-fall trajectory of ultracold atoms via quantum matter wave interference. In recent years, the community's interest in quantum gravimeters has strongly increased as they have progressed from experimental prototypes towards commercially available instruments intended for end-users in geodetic applications.

The commercially available iXblue Absolute Quantum Gravimeter (AQG) B-series instrument is a field-compatible successor to the A-series AQG, which is restricted to indoor use. Here, we present our first results of evaluating the AQG-B10 instrument for lab and field operation in BKG's routine measurement campaigns. We assess the instrument precision, stability, accuracy and reproducibility based on comparison measurements at the Geodetic Observatory Wettzell employing a continuous gravity reference function. This reference is derived from the combination of measurements with the Micro-g LaCoste FG5 FCCG, currently dominating absolute gravimetry, with highly precise superconducting gravimeters, and is linked to the EURAMET.M.G-K3 regional comparison of absolute gravimeters. Moreover, we compare the AQG-B10 to the Micro-g LaCoste A10 FCCG, the current state-of-the-art instrument for absolute field measurements.

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JG07a - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Recent advances in quantum gravity sensors

DOI: 10.57757/IUGG23-2288 - LINK

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Absolute gravity measurements at the level of 10 $nm.s^{-2}$ based on atom interferometry were demonstrated in the laboratory in 1992. Since then, quantum gravity sensors using laser-cooled atoms have received an increasing interest from the geophysics community. Like classical absolute gravimeters, these sensors measure the acceleration of free-falling test masses, atoms, but the working principle relies on the wave nature of matter postulated by quantum mechanics. Quantum gravimeters thus provide a technology inherently different from traditional gravimeters, which can be of interest if absolute measurements are to be checked by alternative technologies.

In 2015, Exail (formerly Muquans/iXblue) launched on the market the first commercial gravimeter based on the quantum manipulation of laser-cooled atoms, the Absolute Quantum Gravimeter (AQG). Exail's cutting-edge technology developments have bridged the gap between the complex academic setups and compact transportable instruments, which reaches the appropriate level of robustness and autonomy to sustain field-deployment. Several units have now been built and deployed for various geophysical applications, including hydrology and volcano monitoring. In this talk we present recent advances in the instrument performances, as well as examples of field-deployment. We focus on a 9-month gravity time series from a site close to the summit of Mt Etna volcano. Through this case study, we discuss the operational advantages offered by quantum technology to the field of volcano gravimetry.

Absolute gravity measurements at the level of 10 $nm.s^{-2}$ based on atom interferometry were demonstrated in the laboratory in 1992. Since then, quantum gravity sensors using laser-cooled atoms have received an increasing interest from the geophysics community. Like classical absolute gravimeters, these sensors measure the acceleration of free-falling test masses, atoms, but the working principle relies on the wave nature of matter postulated by quantum mechanics. Quantum gravimeters thus provide a technology inherently different from traditional gravimeters, which can be of interest if absolute measurements are to be checked by alternative technologies.

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series from a site close to the summit of Mt Etna volcano. Through this case study, we discuss the operational advantages offered by quantum technology to the field of volcano gravimetry.

JG07a - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

BEC quantum sensors for gravimetry on Earth and in space

DOI: 10.57757/IUGG23-4143 - LINK

Waldemar Herr[1], Holger Ahlers[1], Christian Deppner[1], Arne Wacker[1], Baptist Piest[2], Pablo Nuñez von Voigt[2], Nina Heine[2], Jürgen Müller[3], Ernst Maria Rasel[2], Christian Schubert[1]
[1]Deutsches Zentrum für Luft- und Raumfahrt e.V. DLR, Institut für Satellitengeodäsie und Inertialsensorik SI, Hannover, Germany
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Quantum sensors utilising atom interferometry offer new perspectives for future gravity missions. The atom interferometer therein promises long-term stable measurements and high accuracy, complementing or possibly replacing established sensor concepts.

Several different experiments based on this principle demonstrated measurements of gravitational accelerations and gravity gradients. Additionally, dedicated setups showed operation in microgravity environments and tested concepts for future space missions. A core feature of these setups is the robust generation of Bose-Einstein condensates with subsequent matter-wave collimation to generate a well-defined input state extending interferometry times and suppressing error terms.

We will present the state-of-the-art in interferometers using Bose-Einstein condensates, focused on the Quantum Gravimeter QG-1 and our microgravity activities, and discuss concepts for the implementation in future space missions.

Supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) in - Project-ID 434617780 - the SFB 1464 TerraQ within the projects A01, A02 and A03, and under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - Project-ID 390837967.

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JG07b - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Optomechanical inertial sensors for geodesy

DOI: 10.57757/IUGG23-5007 - LINK

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We report on the progress of our novel low-frequency optomechanical inertial sensing technologies for gravimetry and space geodesy. Our technologies are designed to be compact, portable, and are comprised of monolithically fabricated mechanical resonators that incorporate compact and highly sensitive laser interferometric displacement sensors.

Current laboratory prototypes have demonstrated mechanical quality factors *Q* of 4.77x10^5, an *mQ*-product above 1200 kg, a fundamental mechanical resonance of 4.7 Hz, which highlight their high sensitivity with acceleration noise floor nears 1x10^{-11} m s^{-2}/√Hz. Such compact systems are excellent candidates for future applications in gravimetry, geodesy, geophysics, and hydrology.

A prototype packaging has been developed to reduce losses caused by typical mechanical mounts. We have conducted comparison measurements with commercial low-frequency systems to an excellent agreement. Recent measurements taken with the resonator mounted in this packaging atop a vibration isolation platform have indicated that our system is seismically limited above 1 mHz. Noise floors in the order of 82 pico-g/√Hz at 0.4 Hz has been demonstrated in our laboratory.

We will present recent updates on our optomechanical inertial sensors, including up to date measurements of the resonator and interferometer sensitivity, as well as that of the combined system.

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JG07b - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Advances in cold atom interferometer accelerometry and their impact on the sensitivity of gravity missions

DOI: 10.57757/IUGG23-0743 - LINK

Alireza HosseiniArani[1], Manuel Schilling[2], Quentin Beaufils[3], Annike Knabe[1], Benjamin Tennstedt[1], Steffen Schön[1], Franck Pereira dos Santos[3], Jürgen Müller[1]
[1]Institute of Geodesy, Leibniz University Hannover, Hannover, Germany
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[3]Laboratoire SYstèmes de Référence Temps-Espace SYRTE, Observatoire de Paris, Paris, France

Cold Atom Interferometer (CAI) accelerometry is proposed for future generations of satellite gravimetry missions. The technique can achieve high sensitivity and provide long-term stability and precise measurements of the non-gravitational accelerations acting on the satellites. This would reduce the overall instrumental errors and improve the observation of the Earth's gravity field and its change over time and enable a better understanding of several geophysical phenomena, also related to climate change. The current CAI accelerometers have shown great performance, especially in the lower frequencies. They have been able to considerably reduce the bias which is usually seen in the measurements of conventional electrostatic accelerometers. However, noise sources such as satellite rotation can degrade the CAI solution if they are not carefully compensated.

In this study, we model the most impactful error sources which perturb the measurements of a CAI accelerometer onboard a GRACE-like satellite. We further investigate the sensitivity of the instrument to the various error sources, including detection noise, aberrations of laser wavefront, contrast loss due to the Coriolis acceleration and laser intensity inhomogeneity. We also consider the potential improvements which can be expected for satellite-based CAI accelerometers in the near and far future (e.g. longer interrogation time, rotation compensation in different scenarios, and increasing the laser waist). Additionally, we study their potential benefit for future satellite missions and the retrieval of the Earth’s gravity field.

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JG07b - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Cold atom interferometry accelerometry for future low-low satellite-to-satellite tracking and cross-track gradiometry satellite gravity missions

DOI: 10.57757/IUGG23-1438 - LINK

Annike Knabe[1], Manuel Schilling[2], Alireza HosseiniArani[1,2], Mohsen Romeshkani[1], Jürgen Müller[1], Quentin Beaufils[3], Franck Pereira dos Santos[3]
[1]Leibniz Universität Hannover, Institut für Erdmessung, Hannover, Germany
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Satellite gravity missions give unprecedented insights in the Earth system. However, a further improvement in spatial and temporal resolution is required to better monitor the various geo-processes. When considering the sensors of satellite missions, the accelerometers are the limiting factors. Cold Atom Interferometry (CAI) accelerometers are characterized by their long-term stability and an accurate knowledge of the scale factor.

Closed-loop simulations are performed in order to quantify the influence of different accelerometer performances on the gravity field recovery. The impact of the scale factor knowledge on the acceleration measurement is evaluated in terms of a requirement based on the non-gravitational acceleration signal and the accelerometer noise. Furthermore, the variation of the non-gravitational acceleration signal within one interferometer cycle is studied. It is demonstrated that both aspects are significant. The impact on the acceleration measurements can be reduced to an acceptable level by drag compensation. Moreover, the addition of a CAI cross-track gradiometer to a low-low Satellite-to-Satellite Tracking mission is investigated, as supplemental observations in east-west direction are provided. This combination enhances the estimation of the high-degree coefficients and reduces the striping effects in north-south direction.

We acknowledge the support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 434617780 – SFB 1464 and under Germany's Excellence Strategy – EXC-2123 Quantum-Frontiers – 390837967 and the support by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) for the projects Q-BAGS and QUANTGRAV.

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JG07b - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Satellite gradiometry based on a new generation of accelerometers and its contribution to earth gravity field determination

DOI: 10.57757/IUGG23-2361 - LINK

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[3]School of Geospatial Engineering and Science, Sun Yat-Sen University, Zhuhai, China

An accurate model of the Earth's gravity field is beneficial for practical engineering and many applications in geosciences. ESA realized the GOCE gradiometry mission between 2009 and 2013. However, the observation accuracy of the GOCE mission suffered greatly due to the low-frequency drift of the onboard electrostatic accelerometers. Advances in electrostatic and quantum technology offer new measurement concepts for future gradiometry missions. In this study, we evaluate the contributions of several types of accelerometers through numerical closed-loop simulation which rigorously maps the accelerometers' sensitivities to the gravity field coefficients. In comparison to the simulated results of the GRADIO gradiometer used in GOCE, it is demonstrated that the MicroSTAR-type gradiometer has superior precision up to degree and order 100 and provides more signal information in the off-diagonal components of the gradient tensor. The precision of the gravity field model recovery using a hybrid gradiometer that includes quantum technology can benefit from the applied cold atom interferometry (CAI). A hybrid gradiometer with a CAI performance up to 10^-11m/s^2/Hz^1/2 will increase the retrieval of the gravity field remarkably. With an orbital rotation compensation mechanism, the CAI gradiometer can perform with higher accuracy than a classical instrument alone. If not, the accuracy when using the hybrid gradiometer might only be superior up to degree and order 50.

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JG07b - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

GRACE-3D - contribution of angular velocity sensing in the gravity field recovery

DOI: 10.57757/IUGG23-3423 - LINK

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[1]Max Planck Institute for Gravitational Physics, Albert Einstein Institute, Hannover, Germany
[2]Institut für Gravitationsphysik, Leibniz Universität Hannover, Hannover, Germany
[3]Institute of Geodesy, Leibniz Universität Hanover, Hannover, Germany
[4]State Key Laboratory of Geodesy and Earth's Dynamics- Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, China

An important source of noise in the current global monthly time-varying gravity field obtained on the basis of GRACE-like missions (GRACE, GRACE-FO) is the error due to the aliasing of the high frequency non-tidal atmospheric and oceanic mass changes (AOD error). And due to the orbital configuration, the inter-satellite ranging system (K-band ranging system, KBR; laser interferometer, LRI) of gravity satellites is under-sampled in the east-west direction, leading to striping errors in the north-south direction. In our study, we introduced a new independent observational quantity called the angular velocity of the line-of-sight (LOS), i.e. the orientation change of the LOS caused by the gravity field, which has complementary information perpendicular to the LOS obtained from KBR/LRI. We call the combination of angular velocity sensing (AVS) and ranging observations GRACE-3D because it contains three-dimensional gravity observations, not just along the line-of-sight as in GRACE. We developed observation equations for AVS based on the dynamic approach and on the acceleration approach and solved them jointly with the observation equations generated by GPS and KBR/LRI using two independent software suites for cross-validation. The simulation results show that the AVS-based gravity field can reduce the effect of AOD error and significantly improve the north-south strip error when compared to the results obtained using only a combination of KBR/LRI and GPS. And the optimum results are achieved when GPS, LRI and AVS are combined. Finally, We will also briefly discuss how AVS measurements could be obtained in future missions.

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JG07b - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Prospects of Space Geodesy for Atmospheric Moisture and Atmospheric Net-Water Fluxes' Monitoring

DOI: 10.57757/IUGG23-3960 - [LINK]

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Accurate quantification of the atmospheric state is achieved by assimilating numerous and disperse observations into numerical weather models (NWM). The spatio-temporal atmospheric density distribution, a derivative of essential meteorological variables, affects among others how electromagnetic signals traverse Earth's atmosphere and how satellites orbit through Earth's gravity field. Atmospheric refraction in the electrically neutral atmosphere is quantified e.g., during the GNSS data analysis, and holds valuable information about the water vapor distribution in the vicinity of the ground stations. Satellite gravimetry as realized by the GRACE and GRACE-FO missions is sensitive to mass redistribution within Earth's fluid envelope, including but not limited to the atmosphere and the terrestrial water storage, and to high-frequency variations stemming from the time-integrated effect of precipitation and evapotranspiration. In this work we employ two state-of-the-art meso-beta scale NWM (ECMWF's latest reanalysis ERA5 and DWD's operational model ICON-global) as well as ERA5's ensemble members to demonstrate that tropospheric moisture distribution and net atmospheric freshwater fluxes are quite uncertain in modern NWM in comparison to other quantities such as hydrostatic atmospheric mass and that certain space geodetic observing systems such as GNSS and GRACE-FO are appropriate tools to monitor them, thus enhancing the accuracy of numerical weather prediction.

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JG07c - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

CARIOQA-PMP: Developing quantum sensors for earth observation

DOI: 10.57757/IUGG23-3875 - LINK

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for the CARIOQA-PMP consortium

CARIOQA-PMP (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry – Pathfinder Mission Preparation) aims for the development of atom interferometry for a future application in earth observation. Atom interferometers offer the perspective of complementing established sensor technology, implying an improvement in the gravity field recovery.

Whereas quantum sensors based on atom interferometry are studied worldwide and commercial gravimeters are available, the adaptation and qualification for a satellite mission imposes new challenges. Activities in Europe investigating this technology in microgravity facilities show promising results, but are limited by the available microgravity time. Consequently, a pathfinder mission is conceived as the next step towards quantum-sensor-enhanced gravity missions.

Within CARIOQA-PMP, the consortium will develop an engineering model for an accelerometer based on atom interferometry adapted for the accommodation on a satellite. It includes scientists supporting the development and evaluating future mission concepts.

This contribution will outline the background and the scope of the CARIOQA-PMP project.

CARIOQA-PMP is a joint European project, including experts in satellite instrument development (Airbus, Exail SAS, TELETEL, LEONARDO), quantum sensing (LUH, SYRTE, LP2N, LCAR, ONERA, FORTH), space geodesy, Earth sciences and users of gravity field data (LUH, TUM, POLIMI, DTU), as well as in impact maximisation and assessment (PRAXI Network/FORTH, G.A.C. Group), coordinated by the French and German space agencies CNES and DLR under CNES lead. Funded by the European Union.

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JG07c - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

An evaluation of quantum gravimetry satellite missions for quantifying terrestrial water storage variations

DOI: 10.57757/IUGG23-4724 - LINK

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[1]*Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Section Hydrology, Potsdam, Germany*
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Future satellite gravimetry missions may harvest the potential of highly sensitive quantum sensors. The scope of the DLR-funded project Quantgrav is to explore the potential of quantum sensors in space for the analysis of mass variations in the Earth system, towards a better understanding of global change processes such mass loss of continental ice shields and glaciers, changes in global water cycle and budget, or sea level variations.

In this project, different mission scenarios are evaluated, both full quantum gravimetry missions and hybrid missions combining quantum and classical monitoring techniques. In a first step, the error characteristics of potential quantum sensors are described. These are compared to classical observation technologies to determine their benefits. Mission scenarios involving these sensors are then applied in numerical simulations to identify their possible resolution in time and space. The scenarios are then analyzed with respect to their value for science- and service-oriented applications, as a basis for evaluating requirements for a quantum-based gravimetry mission towards a possible future pathfinder mission.

Here we present the results of the evaluation of aforementioned mission scenarios for hydrological applications. The focus is on a) the assessment of error characteristics of the scenarios for resolving water storage variations in the 500 largest river basins worldwide, and b) the potential of these missions to identify extreme hydrological events in these basins, i.e., droughts or floods.

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JG07c - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

The benefit of Quantum technology for future satellite gradiometry missions

DOI: 10.57757/IUGG23-1123 - [LINK]

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The geosciences need to know the mass variations of the Earth with high spatial-temporal resolution and accuracy. Using appropriate sensor technology in optimized satellite missions is essential to monitor the various climate change processes at the required level. Here, it is crucial that novel technologies and dedicated observation concepts for Earth's gravitational field are developed for future missions.

First, we discuss the error properties of various quantum and hybrid gradiometer concepts. Cold Atom Interferometry (CAI) accelerometers and gradiometers exhibit white noise behaviour at low frequencies, making them perfectly complementary to classical electrostatic sensors. We show that accelerometers and gradiometers using atom interferometry, alone or in a hybrid constellation, can dramatically benefit gravity satellite missions. Comparing classical electrostatic gradiometers and CAI-based gradiometers in the spectral domain illustrates the differences of the concepts, also with respect to the GOCE case.

Based on simulated atom-interferometric and hybrid gradient measurements along one or more gradiometer axes in GOCE-like orbits, we discuss the pros and cons of the various approaches.

The geosciences need to know the mass variations of the Earth with high spatial-temporal resolution and accuracy. Using appropriate sensor technology in optimized satellite missions is essential to monitor the various climate change processes at the required level. Here, it is crucial that novel technologies and dedicated observation concepts for Earth's gravitational field are developed for future missions.

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JG07c - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Towards absolute airborne gravimetry using quantum sensors

DOI: 10.57757/IUGG23-5019 - LINK

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for the AeroQGrav consortium

Airborne gravimetry fills the gap between local measurements and global gravity field recovery with satellite missions. In this context, quantum sensors based on atom interferometry offer a new tool for absolute measurements of gravity with the perspective of superior performance in comparison to conventional methods. This contribution will introduce our approach for the concept of the quantum sensor including data fusion to recover the gravity signal, aiming for a resolution of $1\ \mu m/s^2$ after 5 s of averaging.

AeroQGrav is a collaborative research project of iMAR Navigation, Geo++, TU Braunschweig, Leibniz Universität Hannover, Humboldt-Universität zu Berlin, BKG, TU Clausthal, and DLR, funded by the Federal Ministry of Education and Research (BMBF), FKZ 13N16514-21.

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JG07d - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Modeling and simulating of accelerometers and gradiometers concepts

DOI: 10.57757/IUGG23-0583 - LINK

Arthur Reis[1], Alexey Kupriyanov[2], Vitali Müller[1], Jürgen Müller[2], Manuel Schilling[3]
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Geosciences have benefited greatly from the GOCE, GRACE and GRACE-FO missions, especially regarding how the observations of terrestrial mass variations is used to understand and track climate change processes. Furthermore, future gravimetry missions are planned to keep monitoring the static and time variable Earth gravitational field. A limiting factor in gravity field recovery resolution is the sensitivity of the spacecraft's accelerometers, responsible for distinguishing the non-gravitational accelerations from the gravitational signal. Novel accelerometer designs with enhanced sensitivity would therefore be valuable for gravimetry.

To facilitate this venture, we built a tool to model and simulate accelerometers and gradiometers. ACME (Accelerometer Modeling Extended) is a MATLAB/Simulink toolbox that numerically simulates parametrically generated accelerometers and gradiometers, including the dynamics of test mass, capacitances and actuation forces from the electrodes, system frequency response and noise budget (with noise sources such as gas thermal, capacitance sensor, contact potential difference, actuation, and so on). It also includes different sensor models, such as capacitive sensing and laser interferometric readout.

In order to simulate the in-flight behaviour of the instrument, it can be integrated with an orbital dynamics simulator with high-fidelity gravitational field model (XHPS). The generated amplitude spectral densities and mock data series are passed onto gravity field recovery software to evaluate the possible science return. Additionally, simulating legacy instruments allow us to validate the workflow. We'll present the development progress of the toolbox and some illustrative results of what it can achieve.

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JG07d - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Evaluation of optical accelerometry for future gravimetry missions

DOI: 10.57757/IUGG23-0260 - [LINK]

Alexey Kupriyanov[1], *Arthur Reis*[2,3], *Manuel Schilling*[4], *Vitali Müller*[2,3], *Jürgen Müller*[1,4]
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[2]*Albert Einstein Institute, Max Planck Institute for Gravitational Physics, Hannover, Germany*
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[4]*German Aerospace Center, Institute for Satellite Geodesy and Inertial Sensing, Hannover, Germany*

More than 20 years of satellite gravimetry missions have provided unique data about mass redistribution processes in the Earth system. Ongoing climate change underlines the urgent need to continue this kind of measurements with enhanced concepts and sensors. Here, we focus on accelerometers (ACC).

Drifts of the electrostatic accelerometers (EA) are one of the limiting factors in the current space gravimetry missions dominating the error contribution at low frequencies. The focus of this study is on the modelling of enhanced EAs with laser-interferometric readout, so called 'optical accelerometers' and evaluating their performance at Low Earth Orbit (LEO). Contrary to present-day EAs, which measure capacitively the TM displacement and actuate it electrostatically, optical ACC, beside a similar actuation scheme, track the TM with laser interferometry.

Our research is based on promising results of the mission LISA-Pathfinder which demonstrated the benefit of using a drag-free system in combination with optical accelerometry and UV TM discharge which allowed sensing of non-gravitational accelerations several orders of magnitude more accurate than it is realized in current gravity missions.

In this presentation, we now introduce a framework for modeling novel EA with laser-interferometric readout mainly developed by IGP including major noise sources, like actuation noise, capacitive sensing, etc. Also, parametrization of the developed ACC model will be discussed including different TM weights and TM-electrode housing gaps. Finally, improved results of the recovered gravity field will be shown for various mission scenarios applying optical accelerometry and gradiometry.

This project is funded by: Deutsche Forschungsgemeinschaft (DFG) – Project-ID 434617780-SFB 1464.

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JG07d - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Laser Tracking Instrument for Future Gravity Missions

DOI: 10.57757/IUGG23-2705 - [LINK]()

Malte Misfeldt[1,2], Vitali Müller[1,2], Gerhard Heinzel[1,2], Kai Voss[3], Kolja Nicklaus[3], Anne Feiri[3]
[1]Max-Planck Institute for Gravitational Physics, Space Laser Interferometry, Hannover, Germany
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With GRACE Follow-On in orbit for almost five years, developments for the next generation of gravity missions have begun. Firstly, there is the continuation mission of the US-German collaboration that already realized GRACE and GRACE Follow-On. Secondly, ESA is pursuing the so-called Next-Generation Gravity Mission (NGGM) for a launch around 2031. Both pairs are expected to form a constellation with optimized orbit geometry, i.e., a so-called Bender configuration. All of these activities include an improved version of the laser ranging or tracking instrument (LRI/LTI) as the primary ranging instrument, which will be the subject of this presentation.

We will present the operating principle of the LRI/LTI and address the key requirements and challenges of the instruments needed to achieve a ranging noise below the requirement of 40...80 nanometer/sqrt(Hz) for the 200 km satellite separation. We will highlight some of the adaptions needed to evolve the technology demonstrator from GRACE-FO to a primary instrument and discuss the lessons learned so far. Since microwave ranging is not available in future missions, the LRI/LTI scale factor given by the absolute laser frequency needs to be determined by other means, which will also be covered.

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JG07d - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

The Effect of Beam Deformations on Laser-Interferometers in Next Generation Gravity Missions.

DOI: 10.57757/IUGG23-3252 - LINK

Kevin Weber[1], Gudrun Wanner[1], Lisseth Dalia Armas Reyes[1], Gerhard Heinzel[1]
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GRACE Follow-On, the successor of the GRACE mission, continues the legacy of Earth gravity field recovery missions. This experiment's data is an essential contribution to observing and understanding Earths changing climate conditions by, e.g., observing changes in groundwater levels and the mass of ice shields. Activities on successor missions to guarantee an uninterrupted observation of the gravity field are ongoing.
The primary instrument in these missions will be a heterodyne laser interferometer based on the success of the GRACE-FO mission and its superior noise performance compared to the previous microwave ranging. In this talk, we discuss the effect of distorted optical wavefronts on the length readout. We are developing tools to measure the wavefront on ground and extrapolate it over the long distance to the remote spacecraft. We also investigate the potential influence of such distortions together with pointing jitter of the spacecraft.

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JG07d - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

A space-wise approach based on collocation for SST mission data processing

DOI: 10.57757/IUGG23-4180 - LINK

Lorenzo Rossi[1], *Mirko Reguzzoni*[1], *Alberta Albertella*[1], *Batsukh Khulan*[1], *Öykü Koç*[1], *Biao Lu*[1], *Federica Migliaccio*[1]
[1]*Politecnico di Milano, Department of Civil and Environmental Engineering, Milan, Italy*

In the framework of gravity field modelling from satellite mission data, the PoliMi group had designed and developed a space-wise approach based on multi-step collocation, which has been applied to process gradiometric data, like those observed by GOCE. Briefly, this space-wise approach consists of an along-orbit filtering to reduce noise variance and correlation, a local gridding over data patches, and a spherical harmonic analysis by numerical integration; the scheme is iterated till convergence. While the gradiometric observation is directly a functional of the gravity field, with satellite-to-satellite tracking (SST) missions, like GRACE or NGGM/Magic, the main observable becomes a geometric quantity, namely the range or range-rate between pairs of satellites.

To properly process this kind of observables by the space-wise approach, a conversion from the geometric quantity to an along-orbit gravity functional is required. For example, potential can be retrieved by energy balance approach, first derivatives by Hill's equations, second derivatives by exploiting accelerometers on board the satellites as a gradiometer. The space-wise approach has been properly adapted to take one of this functional as input. The main modification is at the gridding level, where suitable covariance modelling is required, also considering the time-variable gravity signal.

The proposed algorithms are applied to different simulated scenarios, assessing the accuracy of the solution by Monte Carlo sampling. In these simulations the payload is considered to be quantum instrumentation, and the performances of the space-wise approach in retrieving both static and time-variable gravity field with gradiometric and SST mission profiles were analysed.

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JG07d - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Comparing GRACE Follow-On Inter-Satellite Pointing Angles from Star Camera and LRI Fast Steering Mirror

DOI: 10.57757/IUGG23-3347 - LINK

Laura Müller[1], Vitali Müller[1], Malte Misfeldt[1], Gerhard Heinzel[1]
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The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission is observing the time variable gravity field by measuring distance variations between two satellites. The first Laser Ranging Interferometer (LRI) between distant spacecraft uses a so-called Fast Steering Mirror (FSM) to satisfy the narrow LRI pointing requirements despite the larger spacecraft pointing variations. The position readout of these mirrors allow to compute the inter-satellite pointing angles yaw and pitch w.r.t. the line-of-sight connecting both satellites. The nominal pointing variations have a magnitude of a few 100 µrad. Typically, the attitude information of roll, pitch and yaw angles is derived from three star cameras and fibre optic gyroscopes.

Since we are particularly interested in the characterization of the FSM at low-frequencies, we compare the FSM readout with star camera measurements for the time-span of December 2018 until December 2022. The residuals show temperature induced changes which are related to the varying orientation of the orbital plane and the sun, expressed through the angle **β**'. We will present our analysis that attempts to attribute and model the residuals.

This analysis is of interest for future gravity missions, where the FSM could be implemented as an additional attitude sensor to control the satellite orientation.

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JG07e - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

A method for measuring gravitational potential on satellite's orbit using frequency signal transfer technique between satellites

DOI: 10.57757/IUGG23-4090 - [LINK]

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We proposed an approach to directly measure the gravitational potential (GP) along the orbit of a satellite, especially for the Low-Earth Orbit (LEO) satellite. The LEO satellite is connected with several Geosynchronous Equatorial Orbit (GEO) satellites through frequency signal links. Arming all the LEO and GEO satellites with precise atomic clocks, the GP difference between LEO and GEO can be measured at any time based on the gravity frequency shift approach. Supposing that the GP of GEO satellites is given, then the GP along the orbit of the LEO satellite can be determined. In this study, we conducted simulation experiments, considering the GRACE-type satellite as the LEO satellite, connected with three evenly distributed GEO satellites. The results show that the precision of the obtained GP along the orbit of the LEO satellite is mainly determined by the precision of onboard atomic clocks. If optical atomic clocks reach an instability level of $1\times10^{-17}\tau^{-1/2}$ (τ in second), the gravitational potential along the orbit of the LEO satellite can be determined at the decimeter level with a resolution of 5'×5'. The GP information along the orbit of an LEO satellite is valuable, for it can be utilized to improve the Earth's gravity models. This study is supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 42030105, 41721003, 42274011), and Fundamental Research Funds for the Central Universities.

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JG07e - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Determination of low-degree temporal variations in the Earth's gravity field using novel optical clocks on-board of low earth orbiters

DOI: 10.57757/IUGG23-3083 - LINK

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The current progress of optical clocks has reached a fractional frequency uncertainty of $1.0\text{x}10^{-18}$ which corresponds to a geopotential difference of 0.1 m^2/s^2. Those gravitational potential differences can be observed as gravitational redshift when comparing the frequencies of optical clocks. Even temporal potential variations might be determined with precise optical clocks on low-orbiting satellites, e.g., at altitudes of SLR-like (e.g. LAGEOS-1/2), GRACE-like and GOCE-like missions.

In this simulation study, the potential of space-borne precise novel optical clocks for the determination of temporal variations of low-degree gravity field spherical harmonic coefficients will be discussed. We will demonstrate that optical clocks at current achievable level of uncertainty are able to reveal long-wavelength seasonal and secular gravity changes. Different configurations of satellite orbits, i.e. at different altitudes (between 250 and 6000 km) and inclinations, are selected as well as certain assumptions on the clock performance are made. We will quantify how well degree-2 coefficients can be estimated from those optical clock measurements and how it compares to results from SLR data.

Keywords: Optical clock measurements in space, temporal long-wavelength Earth's gravity field variations, Relativistic Geodesy

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JG07e - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Terrestrial applications of chronometric geodesy

DOI: 10.57757/IUGG23-0701 - LINK

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The novel method of relativistic geodesy using clock networks has reached an accuracy level that will enable interesting applications in the near future. High-performance clocks with a fractional frequency uncertainty of 10^-18 can detect a gravitational-potential change of 0.1 m^2/s^2 or a corresponding height difference of 1 cm between two clock sites. Here, we explore the advantages of terrestrial clock networks for the detection of time-variable gravity signals and for height system unification by simulations where we consider realistic observation scenarios. On the deformable Earth, terrestrial clock observations contain potential variations due to mass changes and surface displacements. Four case studies were conducted in the Himalayas, Amazon, Greenland, and Fennoscandia to study different mass change processes like seasonal precipitation, present-day ice mass loss, and glacial isostatic adjustment (GIA).

Height system unification involves the estimation of different errors (e.g. tilts and offsets) between the local/regional height reference systems. As a test case, an a priori height system was classified into local systems where various errors have been added. The reunification and estimation of error parameters were carried out using simulated clock measurements. The considered errors include tilts along latitude, tilts along longitude, offsets, tilts that depends upon the distance from the tide gauge, tilts associated with certain levelling lines, systematic noise associated with the elevation of the levelling points, etc. Also, the tidal effects on the clock observations are investigated. Moreover, the optimal number and spatial distribution of the clocks are determined for each scenario.

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JG07e - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Test of determining geopotential difference by precise point position time-frequency transfer using hydrogen masers

DOI: 10.57757/IUGG23-3150 - LINK

Lei Wang[1], Wen-Bin Shen[1], Wei Xu[1], Li-Hong Li[1], Pengfei Zhang[1], An Ning[1], Rui Xu[1], Peng Cheng[1], Ziyu Shen[2]
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According to general relativity theory, the geopotential difference can be determined by comparing the clocks' vibration frequencies or running rates. We conducted experiments to determine the geopotential difference between two remote sites with a height difference of about 1,245 m using two sets of hydrogen maser systems via precise point position time-frequency transfer technique. Two equipment sets were installed at one site or two remote sites to form the local or remote time-frequency transfer link. The gravity frequency shift between two hydrogen masers at two remote sites is derived from the resolved clock offset series, taking into account the local time-frequency transfer link as calibration. Then the geopotential difference is determined as 12,142.3 (112.4) m^2/s^2, quite close to the value 12,153.3 (2.3) m^2/s^2 computed by the EIGEN-6C4 model. Results show that the method proposed here for determining geopotential difference is promising for broad applications. This study is supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 42030105, 41721003, 42274011), Space Station Project (2020)228, and Fundamental Research Funds for the Central Universities (2022).

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JG07e - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Geodetic measurements and quantitative evaluation for reduced gravitational redshift uncertainty of optical frequency standards

DOI: 10.57757/IUGG23-0456 - LINK

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[1]National Institute of Information and Communications Technology, Space-Time Standards Lab., Koganei, Japan
[2]Geospatial Information Authority of Japan, Geodetic Department, Tsukuba, Japan
[3]National Institute of Polar Research, Division for Advanced Research Promotion, Tachikawa, Japan
[4]University of Tokyo, Earthquake Research Institute, Tokyo, Japan
[5]Mount Fuji Research Institute, Division of Volcanic Disaster Mitigation Research, Fujiyoshida, Japan
[6]Kyoto University, Geodesy Laboratory, Kyoto, Japan

The National Institute of Information and Communications Technology (NICT) has developed a Sr optical lattice clock and optical ion clocks employing In+ and Ca+. The centimeter-level uncertainty of site elevation is the cause of 10^(-18)-level frequency uncertainties of optical frequency standards. It is significantly important to understand frequency changes caused by solid-earth tides that often range from 10 to 20 cm in amplitude, by oceanic tidal loading, crustal deformations due to earthquakes, and ground movements with groundwater changes for the stable operation of optical atomic clocks.

NICT and partners including the Geospatial Information Authority of Japan (GSI) have been jointly conducting leveling surveys and relative gravimeter observations at NICT's headquarters in Koganei. These observations reduce the contribution of gravitational redshift to the total uncertainty of the optical lattice clock to the 10^(-19) level. With the support of National Institute of Polar Research (NIPR), absolute gravity measurements were performed in August 2019 and May 2022 to evaluate the effects of the 2011 off the Pacific coast of Tohoku Earthquake on postseismic crustal movement. The obtained absolute gravity change between the two periods was -43.8 μGal, which matches the trend of GNSS vertical movement obtained by GSI. We have introduced a Micro-g LaCoste's gPhoneX gravimeter for continuous gravity measurements nearby the optical clocks in the end of 2021 and have started to investigate the temporal variation of the ground water level in Koganei. We will present preliminary results of these geodetic measurements.

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JG07e - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Towards Clock Ties for a Global Geodetic Observing System

DOI: 10.57757/IUGG23-2639 - LINK

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International reference frames are cornerstones for all metrological applications related to Earth sciences covering global change research, global deformation, and mass transport. Over the last two decades, the precision of underlying measurements on which the reference frame is based improved to a millimeter level. However, the overall achieved accuracy remains at centimeter-level errors. In this contribution, we will introduce a promising approach examining imperceptible error sources which influence all types of measurement equipment and which are not captured by any calibration. To make them visible, combinations of different kinds of techniques are needed. The recently established DFG funded research unit “Clock Metrology” introduces the new measurement constraint based on accurate optical clocks to demonstrate the direct measurement of a physical height difference between the Geodetic Observatory Wettzell and the Physikalisch-Technische Bundesanstalt based on optical time transfer. The investigation of systematic errors is based on the introduction of a new timing tie into a measurement and analysis process, guaranteed by the preservation of clock coherence used for systems calibration. Within this research unit, we will develop a new calibration technique that expands local coherence to the measurement process of satellite positioning. We will achieve this by transmitting an artificial Galileo signal preciously synchronized to a common clock.

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JH01a - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

FAIR data for enriched reuse of data compilations

DOI: 10.57757/IUGG23-4611 - LINK

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Reusability of research data is one of the four FAIR principles. Envisioning future data reuse scenarios early in the data life cycle requires anticipation, since data reuse is often not carried out by the data producers, and reuse scenarios are constantly evolving. Data reuse is especially challenging when the data reuser is active in a different domain than the data producer. The application of data science methods, for instance, poses a growing demand on the (meta-)data information quality. In Earth Sciences, the development of data-driven models or data-integrated predictive simulations often first requires to assemble a homogenous and sanity checked data compilation as training data, which is made up of individually heterogeneous and non-consistent data sets. In order to do that in an efficient way the data sets have to comply with the FAIR paradigms. Here, we share our experience from creating a data compilation from sea ice core data with focus on temperature and salinity measurements. First, we will report on the FAIRness of publicly available sea ice data. The heterogeneous character of the data morphology and metadata availability makes interoperability challenging and reuse laborious. To overcome these deficiencies, we developed a workflow to create data compilations. We will conclude with a descriptive analysis of the sea ice core data compilation.

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JH01a - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

FAIR assessment: A subjective qualitative interpretation or a domain-specific and quantitative measure?

DOI: 10.57757/IUGG23-4389 - LINK

Angelo Strollo[1], Susanne Hemmleb[1], Laura Hillmann[1], Peter Evans[1], Javier Quinteros[1], Robert Huber[2], Florian Haslinger[3]
[1]GFZ German Research Centre for Geosciences, Geophyiscs, Potsdam, Germany
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[3]ETH Zürich, Swiss Seismological Service, Zürich, Switzerland

Findability, Accessibility, Interoperability and Reusability have become important principles in the geoscience community as it makes standardisation and openness a priority, so that these keywords are nowadays in focus for any new project at institutional, national and international levels. In seismology and its community that uptake has been extremely rapid and the level of FAIRness reached can be considered well above average within geoscience. But what "well above average" means and how to quantitatively assess FAIRness within this domain and compare seamlessly to others remains challenging.

Taking advantage of ongoing national and international projects, a group of data managers from the EPOS seismological community started a collaboration with the FAIR-IMPACT project and its F-UJI developers aiming at enhancing the FAIR assessment process for specific domains. The group went through a process of mutually increasing awareness and understanding of FAIR definitions and their interpretations, including machine readability. Outcomes included F-UJI developers becoming more aware of the overall granularity and conception of research datasets including standard data and metadata formats used in seismology; revisions to landing pages; and updating guidelines to harmonise DataCite metadata for datasets within the domain.

In this presentation we outline the liaison process established by the seismological data managers with F-UJI and introduce the first outcomes. We present the initial guidelines developed, a summary of selected FAIR assessments and finally we propose to further discuss FAIR assessment within the seismological formal governance body, namely the International Federation of Digital Seismograph Networks (FDSN) as a commission of IASPEI.

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JH01a - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Metadata mapping between disciplinary and general schemas for promotion of data use by a wider community

DOI: 10.57757/IUGG23-1480 - LINK

Masahito Nosé[1], Atsuki Shinbori[1], Yoshizumi Miyoshi[1], Tomoaki Hori[1], Tsukasa Oohira[2], Junko Hashiba[2], Chizuko Naoe[2], Maiko Okamoto[2], Takeshi Sagara[3], Takaaki Aoki[4], Ichiro Takahashi[4], Hidekazu Hayashi[4], Kazunari Yamada[4], Yoshimasa Tanaka[5], Shuji Abe[6]
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[6]Kyushu University, International Research Center for Space and Planetary Environmental Science, Fukuoka, Japan

In the Inter-university Upper atmosphere Global Observation NETwork (IUGONET) project, we have been creating metadata for ground observation data in space physics and populating them into the database since 2009 (http://www.iugonet.org/). These metadata followed the IUGONET metadata schema version 2.4.0.1, which is an extension of the SPASE (Space Physics Archive Search and Extract) metadata schema version 2.4.0.The IUGONET metadata database is very useful for researchers to search for data that they need and to obtain detailed information about data, but the metadata search is available only through the IUGONET page or NASA Heliophysics Data Portal. To promote data usage by a wider research community or the general public, it is needed to convert the metadata database from SPASE to more general schema so that the metadata can be ingested into other metadata databases. For that purpose, we developed a mapping table from SPASE to the JPCOAR (Japan Consortium for Open Access Repository) schema, which has been widely used for scholarly communication and data publication in Japan. Based on the mapping table, we converted part of our metadata, which describe data created in Nagoya University, to those in the JPCOAR schema. The converted metadata were registered in the institutional repository of Nagoya University (https://nagoya.repo.nii.ac.jp/). These metadata are consequently harvested by Institutional Repositories DataBase (https://irdb.nii.ac.jp/), Data Catalog Cross-Search System (https://search.ckan.jp/), and Google Dataset Search (https://datasetsearch.research.google.com/). We plan to do the same action for the other IUGONET metadata. This will significantly enhance findability and accessibility of the IUGONET metadata and their describing data.

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JH01a - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

GeoNet New Zealand: Recent Open Data and other key Initiatives

DOI: 10.57757/IUGG23-2193 - LINK

Jonathan Hanson[1], Elisabetta D'Anastasio[1], Joshua Groom[1], Mark Chadwick[1], Jerome Salichon[1], Elizabeth Abbott[1], GeoNet Programme Team[1]
[1]GNS Science, Data Science and Geohazard Monitoring, Lower Hutt, New Zealand

Aotearoa New Zealand's GeoNet programme was launched with an open data framework to support research, monitoring, and geohazard response at its core. Open data has proven to be hugely successful for GeoNet funders and user community and continues to be at the heart of GeoNet. GeoNet is now evolving to develop new services, storage, processing, and dissemination mechanisms to meet emerging data usage requirements (for example: requests to access large data volumes).

Over the last few years, GeoNet has taken some major steps forward in supporting data access, usability, and resilience in data operations:

- GeoNet moved its diverse data collection, processing and storage to the cloud (Amazon – Web Services). This includes the development of a data lake strategy;
- GeoNet released TILDE, a system to disseminate low to medium sample rate datasets in a common format, that supports access via an Application Programming and a Graphical User Interfaces;
- GeoNet partnered with AWS Open Data Sponsorship Programme to make a copy of its data freely available for large data query access.

GeoNet continues to face other challenges: understanding and tracking impact and data use (user registration and authentication for data access?), quality monitoring, adoption and impact of new initiatives (e.g. citizen science), improving integration of Te Ao Māori, and significant expansion of data volumes and variety. But with challenges come opportunities and GeoNet looks forward to working with the broader international community and fostering discussions to how best to balance data funders/providers/users needs whilst keeping open data as a core principle.

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JH01a - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

How to bridge data knowledge gaps in hydrology? A priority area in the new phase of UNESCO-IHP (and beyond).

DOI: 10.57757/IUGG23-4656 - LINK

Stephan Dietrich[1], Luna Bharati[1], Matthias Zink[1], Philipp Saile[1], Claudia Färber[2], Looser Ulrich[2], Harald Koethe[1]
[1]Federal Institute for Hydrology,
International Centre for Water Resources and Global Change, Koblenz, Germany
[2]Federal Institute for Hydrology, Global Runoff Data Centre, Koblenz, Germany

The need for improved data and information exchange in freshwater-related observations has been a long-standing issue for scientists. Despite progress in hydrological cycle observations, the Global Climate Observation System (GCOS) still identifies the need for improvements in data exchange. We summarize past and recent efforts to improve data sharing globally and regionally, focusing on technical efforts and agendas at UN level. The main barriers are known and related to a) lack of capacity to apply international standards for data and metadata exchange and b) restrictive data policies that hinder data exchange. To bridge these data knowledge gaps we will introduce a subtopic of the IX. phase of UNESCO-IHP, the Output 3.3 dealing with “Comparing and validating open access data on water quantity, quality and use and their sharing by the scientific community supported for sustainable water management.” The presentation covers

- recent developments by the WMO in advocating for open data policies and improving interoperability, including the role of globally operating data centers federated in the Global Terrestrial Network - Hydrology (GTN-H). We will provide insight into recent efforts of the GEMS/Water Data Centre to improve interoperability of water quality data and show the success of the GRDC in implementing a new data portal,
- a report on the UN 2023 Water Conference and its focus on sharing water observation data to achieve SDG6 goals.

The presentation additionally aims to encourage discussions on how to improve scientific data comparison and cross-validation across domains by facilitating standards to improve compatibility and harmonization across teams and disciplines.

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JH01a - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Reprocessing of XBT profiles from the Ligurian and Tyrrhenian seas (1999-2019) with full metadata upgrade

DOI: 10.57757/IUGG23-4933 - LINK

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[4]Chinese Academy of Sciences-, Institute of Atmospheric Physics, Beijing, China

The open data paradigm spurred the sharing of data through different pathways determining the generation of different versions of the same datasets. This might depend on different factors: the data delivery process, the data center managing the dataset or the marine data infrastructure collating it.

A data provider should define a data quality assurance and long term curation strategy along with the data lifecycle, which implies the possibility of reprocessing a dataset according to the latest quality control procedures and standards. To this, it is important to combine data with complete metadata description allowing interoperability, traceability and transparency of the information process. In particular, some key metadata is crucial in climate science because it allows to re-analyze historical data, quantifying and reducing uncertainties of key ocean monitoring indicators such as the Ocean Heat Content.

The objective of this work has been to reprocess all the raw data and metadata available from about 3800 XBT (eXpendable BathyThermograph) probes launched in the Ligurian and Tyrrhenian Seas between 1999 and 2019 by applying an improved delay mode and almost completely automatic quality control procedure. The dataset contains the most complete set of metadata collected during the monitoring activity, not available in any previous data version. The data has been encoded and formatted following the latest community standards and FAIR principles with the aim of implementing an operational workflow for the new monitoring activities and the Near Real Time delivery of data through ERDDAP server.

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JH01b - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Integration of biophysical data in a hydrologic knowledge graph precursor for water and carbon tradeoffs

DOI: 10.57757/IUGG23-4784 - LINK

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Data integration and analytics platforms play a critical role in better understanding natural systems and laying the foundations for modeling them as complex adaptive systems—for example, how carbon and hydrological cycles can track the functionalities of (agro)ecosystems. Also, the resultant databases and other digital resources are the precursors of knowledge graphs. Nonetheless, data-driven models have become widely used in water resource planning and management; these models require datasets that incorporate the diversity and variability of patterns that occur in nature, including those driven by land use, crop management, and climate variability and change, for model generalization. Further, the use and integration of data can be constrained to a few sources due to the availability of datasets and the time, skills, and efforts required to blend multi-disciplinary heterogeneous datasets. The main goal of this study is to integrate biophysical variables (crop, land cover and soil information) to the recently designed open-source web platform. The objectives are to (1) design a job schedular for data retrieval at the regular temporal interval, (2) data preprocessing, quality control, and data integration pipelines, (3) design of NoSQL (MongoDB) database for a flexible, efficient, and reliable data storage for heterogeneous and semi-structured datasets that support parallel processing and complex geospatial queries for data analytics. We expect to foster the exploration of the underlying biophysical processes associated with the intensity of the intertwined carbon and water cycle and eventually a better management of carbon budgets by developing and training data-driven models and analytics for stakeholders and decision-makers.

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JH01b - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

The Global Runoff Data Centre – Facilitator between data providers and the hydrological research community

DOI: 10.57757/IUGG23-2838 - [LINK]

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River systems are an integral part of the water cycle. Observational runoff data are fundamental for the sustainable management of water resources and for the validation of hydrological models across all scales.

The Global Runoff Data Centre (GRDC) operates under the auspices of the World Meteorological Organization (WMO) at the German Federal Institute of Hydrology (BfG). Established in 1988, it holds the most substantive collection of quality assured river discharge data worldwide. GRDC has been a key partner in a number of data collection and data management projects and provides the link between national hydrological and hydrometeorological services and the international research community.

Currently, the Global Runoff Database contains river discharge data collected at daily or monthly intervals from more than 10,000 stations in 160 countries, dating back up to 200 years. As a trustworthy source for runoff data, GRDC has been integrated into the WMO Catalogue for Climate Data, supporting climate research and environmental risk assessment. In addition, GRDC provides different sets of geospatial data products that have formed an important basis for various modelling studies. As the awareness for open data and reproducibility has increased in recent years, GRDC is working to simplify data provision to its users. GRDC data and products are accessible online for non-commercial use (https://grdc.bafg.de/). However, there are still hurdles on the way to a completely open and free exchange of data such as restrictive data policies and a lack of data standardization.

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JH01b - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Turning publications into data – imagining a world of linked hydrologic knowledge

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As a science, hydrology faces diverse sets of interacting processes combined with a vast heterogeneity of our environment. Ideally, one would be broadly knowledgeable in all processes of the water cycle, but taking such a holistic approach to our science has become problematic due to the vast number of hydrologic case numbers published. Exponential publication numbers make it impossible to keep up with the current literature, not to mention the knowledge acquired over time.

These publications comprise a vast source of information and data that is not being utilised at the moment. One solution that has been discussed is to extend our article metadata to relevant hydrologic information in support of search and synthesis of hydrologic knowledge. There is a wide range of relevant metadata: for example, research topic, study location, models used, time period covered, data availability…. In regard to data services, it could be used to link data collections or networks with the models that use that data, the researchers who employ the models, and the publications that summarise the knowledge gained.

For this data to be useful and used by the community, it will need a collaborative platform to host this information. We discuss the use of Wikidata, a free, accessible, machine-readable, and editable by all, database, for this task. An added benefit is that Wikidata can easily link to existing data repositories and persistent identifiers, thus making the concept not only of interest for article metadata but also a potential interoperable approach for data services.

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JH01b - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Advancing frontier knowledge of the solid earth by providing access to integrated and customized services: the Geo-INQUIRE project

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[12]LMU, Department of Geophysics, Munich, Germany

Modern scientific endeavours already have the capacity to call upon a vast variety of data, often in huge volumes. However, the challenge is not only how to make the most of such a resource, but also how to make it available to the wider scientific community. Fifty-one institutions from 13 countries are currently working together in the Geo-INQUIRE (Geosphere INfrastructure for QUestions into Integrated REsearch) project.

The goal of this new project is to enhance, give access to, and make interoperable, key datasets of the Geoscience community. This will include "big" data streams and high-performance computing codes which are critical to studying the temporal variation of the solid Earth, forecasting multi-hazards, evaluating Georesources and the analysis of the interface between the solid Earth as well as oceans and atmosphere. About 150 access points – both on-site and virtually are involved.

Several European Research Infrastructure Consortia take part, namely the European Plate Observing System (EPOS) for solid Earth and geodynamics observations, the European Multidisciplinary Seafloor and Water Column Observatory (EMSO) for deep-sea and coastal observations, and ECCSEL for CO2 capture, utilization, transport, and storage, and geoenergy. This 16 million Euro project started in October 2022, within the Horizon Europe Infrastructure program.

The presentation will briefly describe the project and give examples of curiosity-driven research topics which will be made possible through such a multi-disciplinary project. We will finally present the challenges and efforts made to comply with FAIR principles and accompany the dissemination of the data with innovative and cross-disciplinary training activities.

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JH01b - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Harmonized oceanographic cruise databases for connecting ocean datasets

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First steps towards digital oceans rely on connecting datasets, harmonizing criteria and providing data access to wider user communities, but along the time, different storage codes have been adopted by the data providers according their own needs. The National Oceanographic Data Centre (NODC) is performing a strong effort in order to unify its datasets, making easier their identification and access. In the framework of (International Oceanographic Data Exchange, (UNESCO/IOC/IODE) initiatives, the IEO maintains a standardized catalogue of oceanographic surveys (CSR), integrated in international repositories as SeaDataNet or POGO. Although this activity has suffered ups and downs over 50 years of activity, the updating results sums up more than 4000 entries, including foreign surveys in national waters.

Linked to it, the whole discrete water sampled analysis dataset has been renamed, profile by profile, following the same adopted naming criteria that CSRs. This assesses the uniqueness, prevent duplicates an improve their accessibility. More than 16000 profiles have been revised and updated following this approach, improving data access and allowing better storage protocols. The initiative accomplishes the european adopted criteria for metadata and data storage formats. A Geonetwork -OGC standard- catalogue possibilities the access to this information and data to a wide end-users community.

As a case study, the information of the monthly standard oceanographic section of A Coruna (NW of Spain) is implemented in a local Geonetwork catalogue. Information about cruises and profiles is freely available. The technological harvesting capacities and machine to machine connections, increases the data visibility and reusing.

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JH01b - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Quality control procedure and bias assessment for the global oxygen profile dataset

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Global archive of dissolved ocean profile data is characterized by a high degree of heterogeneity with data obtained both by the Winkler chemical titration method and by different electrochemical and optical sensors. Respectively, the accurate assessment of the secular change of the oxygen content critically depends both on the quality control of oxygen data and the estimation of the sensor data bias relative to the reference Winkler method data. Based on the earlier studies on data quality control within the International Quality-Controlled Ocean Database initiative (IquOD) we developed the quality control procedure for the ocean oxygen profile data and applied it to the global World Ocean Database. Selected high quality oxygen profiles were used to estimate the effectiveness of the procedure in identifying data outliers. Analysis of data outliers reveals significant differences in data quality between the Winkler method and sensor data with data from CTD profiles showing higher outlier percentages compared to the ship-based Winkler method data and data from Argo floats. The co-located quality controlled oxygen profiles were used to estimate systematic offsets between the sensor and Winkler method data. We find significant time-varying negative overall oxygen offset for Argo oxygen profiles, with mean offset decreasing from about -10 to -12 mkmol/kg before 2010 to -5 mkmol/kg after about 2015.

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JH05a - Citizen Science, Crowdsourcing and Innovative Monitoring for Advancing Geo-Sciences (IAHS, IASPEI, IAGA, IACS, IAMAS)

Citizens AND HYdrology (CANDHY): On the application of a framework for benchmarking citizen science projects in hydrology

DOI: 10.57757/IUGG23-3998 - LINK

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The CANDHY Working Group (WG) by IAHS aims to foster scientific exchange among academic, institutional, business and citizen communities by promoting discussion and sharing of knowledge, information, data, and ideas related to "Citizen AND Hydrology". CANDHY seeks to harness the potential of citizen involvement and crowdsourced data to advance hydrologic research on water resources management, hydroclimatic risk mitigation, and disaster preparedness. Indigenous knowledge and new data coming from increasingly accessible mobile technologies are some of the topics of interest of the Group. CANDHY aims to join efforts with social sciences in identifying novel frameworks for integrating diverse socio-cultural and demographic dynamics, citizen perception and behavior into hydrological study. CANDHY promotes studies that engage citizens as human sensors and management actors of hydrological and societal change.

The first CANDHY community paper presented a novel framework for benchmarking citizen science projects in hydrology. This community paper conceptualized the application of the framework for assessing citizen science projects of interest for the hydrological and geophysical sciences. The framework may be visually represented by a radar plot, which provides a schematic visualization of the benchmarking and assessment framework to selected citizen science projects.

The CANDHY working group is interested in merging efforts with social sciences and humanities for the 2nd community paper to co-identify citizen science projects and co-test the novel benchmarking framework. Particular interest is on sharing and transferring available knowledge, science and approaches for citizen and stakeholder engagement, cultural and behavioral change in addressing hydro-climatic challenges.

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Developing a Catalog of Open and Free Datasets for Hydrologists: A Crowdsource Initiative

DOI: 10.57757/IUGG23-3755 - LINK

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Data collection and management constitutes the foundation for all analysis and modeling tasks required for achieving water, food, energy, and environmental security. UN-Water identifies data and information as one of the five accelerators where efforts and investments should be concentrated to achieve the Sustainable Development Goal 6 (SDG 6). Availability of open and free data resources can greatly contribute to enhanced implementation capacity in water research. In this context, it is crucial that data are freely accessible, openly available, and reliable. Open datasets are available online, are accessible in machine-readable formats (i.e. not pdfs or reports), and are obtainable by the public. Free refers to the availability of datasets with licenses that allow sharing at no cost to individuals, researchers, institutions, or projects. However, such datasets are dispersed across various websites and repositories. This hampers visibility and findability, which in turn results in limited use for generation of new knowledge or transferability of insights. This highlights a critical need for improving visibility of existing hydrological datasets, dedicated projects, and repositories. Crowdsourced scientific data collection efforts enable collaborative work and provide potential solutions to these issues. In this talk, we present a crowdsourced hydrology initiative aimed at establishing a global catalog of open and free datasets. This inventory will provide a database of static links, data DOIs, description of datasets along with key references and supporting information. We report on our progress and challenges in designing such an initiative with the hope that others will benefit.

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JH05a - Citizen Science, Crowdsourcing and Innovative Monitoring for Advancing Geo-Sciences (IAHS, IASPEI, IAGA, IACS, IAMAS)

Advancing innovative hydrological monitoring

DOI: 10.57757/IUGG23-4992 - LINK

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Business as usual is no longer an option in view of seriously engaging in the sustainable development agenda and robust climate action. The call from the UN Secretary General for providing early warnings for all within 5 years is a further incentive to act. These undertakings all require reliable, available and accessible hydrological data. To meet this need, many current hydromet monitoring systems need optimization of their efficiency and cost. Here, existing emerging technologies and approaches, including Artificial Intelligence, Internet of Things and Citizen Sciences offer new opportunities. Their operational uptake by National Meteorological and Hydrological Services (NMHSs) is however currently low, for various reasons including lack of trust and insufficient dialogue between innovators, hydromet services and their user communities.

In view of this, the WMO HydroHub offers a mechanism to support the operational uptake of existing and emerging technologies and approaches in a sustainable way, through partnerships, and by providing actors with capacity, innovation and engagement possibilities.

This Keynote will highlight some concrete examples of innovation-related activities the WMO HydroHub is taking forward. These include Innovation Calls, which identify and operationalize innovative solutions to hydrometric challenges, as well as Innovation Workshops, which bring together NMHSs, academia, private sector and others in view of better tailoring solutions to operational realities and directing research towards more pertinent topics. Other activities showcasing how the WMO HydroHub leverages multistakeholder dialogue platforms to generate ideas and synergies to tackle challenges will also be highlighted. Innovative ways to strengthen the sustainability of solutions will also be discussed.

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JH05a - Citizen Science, Crowdsourcing and Innovative Monitoring for Advancing Geo-Sciences (IAHS, IASPEI, IAGA, IACS, IAMAS)

Measuring weather data with a self-build low-cost sensor

DOI: 10.57757/IUGG23-4159 - LINK

Vincent Sobottke[1], Daniela Schoster[1], Henning Rust[1], Christopher Böttcher[1], Jonas Lehmke[1], Jana Ulrich[2], Marco Otto[2], Fred Meier[2]
[1]Freie Universität Berlin, Statistische Meteorologie, Berlin, Germany
[2]Technische Universität Berlin, Klimatologie, Berlin, Germany

Considering the fast urban growth and the rapid increase of the city population, urban areas are constantly changing. Additionally, the spatial heterogeneity of Berlin leads to a pronounced spatial variability of meteorological variables, which is impossible to capture with the existing network of urban measuring stations. Therefore, the Open Urban Climate Observatory Berlin aims to establish an open meteorological measurement network by involving the urban society, e.g. allotment gardeners, who maintain the measuring devices especially developed for this purpose. With this extension of the classical measurement network and a recently installed high-resolution precipitation radar for Berlin, a new data basis becomes available to answer relevant questions for the urban community.

In order to improve the quality of this data set, we apply a range of methods from the fields of Statistics and Machine Learning to filter faulty measurements and calibrate measurements using publicly available data from stations of the German-Weather-Service (DWD) and the network itself.

In collaboration with the citizens, research questions will be developed and addressed and the potential of possible applications will be explored during workshops. In this process, citizens will be supported by scientific staff with technology and knowledge about the urban climate. Ideally, the results will serve as a basis for the development of applications, e.g. a digital watering assistant that provides watering recommendations optimized for plant growth and resource utilization based on local measurements and appropriately processed precipitation forecasts.

We will report on the current status of the project and some preliminary results of data analysis.

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JH06a - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

What makes science-and-policy-dialogue successful? Impact analysis of a parliamentary evening in the German Bundestag

DOI: 10.57757/IUGG23-4046 - LINK

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The term “Science-and-policy-dialogue” in contrast to “Science-to-policy-advise” indicates the need for a dialogue instead of a one-way-advice. Our communication must be needs-based, addressing what’s on the political agenda. The objective is science-based policymaking, which means politicians use high-quality information to inform political decisions. While science-and-policy dialogues face many challenges – e. g. different focal points and timelines of research and politics, no prospect of higher scientific reputation – they are worth the effort because, for apparent reasons, trial-and-error is not an option in Earth system politics.

SynCom is the overarching synthesis and communication platform of the research field 'Earth and Environment' of the Helmholtz Association. SynCom synthesizes research results and builds bridges across various disciplines. Functioning as an interface between science and society, SynCom supports evidence-based climate and environmental politics.

In this talk, I will present the results of an impact analysis of a parliamentary evening on the "climate-resilient city", which we held in November 2022 on the dome of the German Bundestag.

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JH06a - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

The Ice Age machine

DOI: 10.57757/IUGG23-3190 - LINK

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Over the last million years, cyclical changes in Earth's orbital parameters have been responsible for climate fluctuations and ice ages that have shaped our landscape. Current climate change, on the other hand, is caused by human greenhouse gas emissions and the CO2 content in the atmosphere exceeds the maximum value of the last 800,000 years by far. This is the main cause of current global climate change, which will affect human beings, and the whole ecosystem far into the future.

While public awareness of climate change has increased massively over the last years, many misconceptions are still widespread. In order to increase awareness about the human impact versus natural processes, we are designing an interactive «Ice Age Machine», which will be placed at popular vantage points in Switzerland from September 2023 onwards. These interactive stations will allow groups of users to actively experience past ice ages as well as the corresponding environmental changes thanks to an innovative design and new visualization techniques based on artificial intelligence. The visitors will learn about the history of glaciations in the Alps, the extreme impact of human being on climate and what the future effects could be. The users have the opportunity to retrieve a photo showing them in action at the station in front of the panoramic ice age view to share via social media. To increase the visibility of the machine beyond the vantage points, communication activities on site and in the digital space (website, social media) will accompany the project.

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Experiencing climate change: Environmental education and public relations on vanishing glaciers

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While interest and societal impact of climate science/geoscience increases, the accessibility of research results and knowledge decreases as a result of publication strategies: Articles published in scientific journals often do not use a common language, and scholarly knowledge is needed to understand the often very specific content. Teaching books in national languages are very rare in 21st century. Therefore, the gap between scientific frontier and basic education widens, leaving room for science sceptics or fake news, for example denying anthropogenic climate change in social media.

Environmental education helps to get in touch with the methods and results of geosciences. Several thousands of pupils participate in field courses and classroom activities of the National Parks. TV productions, podcasts, online and print media articles reach a much higher percentage of the population as the most popular high ranking journal article does.

To ensure that science prolongates it’s story of success, and being convincing for all people, the dissemination has to be broad. We established a science education centre right at Jamtalferner, an WGMS benchmark glacier and LTER site to foster the communication of scientific results together with the local museum and community, in cooperation with local guides https://www.umweltbildung-jamtal.info/. In the last years, media interest increased, and the interdisciplinary research has been subject of several press trips. We consider this an important part of scientific work, despite the lack of specific funding.

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The WormEx II experiment to raise awareness about the importance of healthy soils and of their hydrological functions

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Healthy soils provide many ecosystem services, among which some relevant ones belong to the hydrological sphere. In fact, healthy soils feed and filter freshwater reserves, whereas degraded soils can pollute water resources and make them unavailable or harmful to humans and plants. Besides, healthy soils are effective for both climate change mitigation, being the largest terrestrial carbon pool on the planet, and adaptation, thanks to their capacity of absorbing and retaining water thus reducing the hazard of floods and droughts.
However, these characteristics are nowadays endangered due to several challenges deriving from mismanagement of the limited soil resources, the consequent soil degradation phenomena (viz soil sealing, erosion, loss of biodiversity and of organic matter) often lacking the necessary awareness and visibility.
Aiming at contributing to disseminate the importance of healthy soils for the society and at highlighting the hydrological functions of an healthy soil, we designed the WormEx II experiment, that is an educational experiment to be performed in high-school classes. The experience takes the participants along the footsteps of Charles Darwin, who, studying the activity of worms, showed how great changes in Nature are often the result of the continuous superimposition of minimal processes. Researchers, teachers, high-school and university students set up a participatory experiment to repeat Darwin's observations on the ability of annelid digging activity to bury abandoned bodies on the soil surface. By this experiment, students will observe how soils with different annelid activity behave and how the annelid activity increases the soil infiltration capacity.

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Seismic risk communication over the past 20 years: An overview of european publications

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The widespread lack of awareness of seismic hazard and the inadequate preparedness to protect people and property explains the high cost of damage caused by earthquakes worldwide to date. Efficient communication is of paramount importance as part of effective risk mitigation strategies. Over the past twenty years, efforts have been pursued at the local, regional, national, and international level to disseminate information on seismic hazard to populations at risk.

Focusing on Europe, we analyze the main features of seismic risk communication from 2000 to 2022, and present here an overview of the results obtained based on a scoping review of the scientific literature. Our review was conducted on publications selected from Scopus, Web of Science, and Google Scholar databases and the information was gathered on the basis of the 5 'Ws questions' (Who, What, When, Where, and Why). Overall, the selected publications document the relatively limited engagement of the scientific community in this risk field compared to other natural disasters. Nevertheless, the growing trend over time of publications dealing with seismic risk communication highlights the effort to attract selected targeted audiences (particularly children), using new contents, methods of implementation, and channels such as social networks and the Internet.

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The transdisciplinary design of user-centred seismic risk products to increase societies' resilience towards earthquakes – the Swiss case

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Worldwide, there is a shift from hazard to risk communication in order to increase societies' earthquake risk awareness and, consequently, their willingness to take protective actions. So far, little research has been conducted on how to design user-centred seismic risk products, which would allow societies to take informed decisions. Only if well designed and tailored to the end users' needs, these products have the potential to increase societies' risk awareness and, in turn, their resilience towards earthquakes.

We thus applied a transdisciplinary approach by co-designing with experts from different disciplines multiple versions of rapid impact assessments, earthquake risk scenarios, and seismic risk maps, which we then tested with the Swiss public and professional stakeholders of the society (e.g., authorities, civil protection). To this end, we conducted several workshops with professional stakeholders in 2021 and two surveys with the Swiss public in 2022 and 2023. The surveys both contained a between-subjects experiment, which allowed us to assess which version of the products is correctly understood, best perceived, and triggers people to take protective actions.

At the conference, we will present the results of those studies and provide evidence-based recommendations on how to design user-centred rapid impact assessments, earthquake risk scenarios, and seismic risk maps. This should support institutions responsible for public communication to add risk products to their communication strategy to effectively inform the society about seismic risk and, consequently, increase their risk awareness and intention to take protective actions.

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Bimbim's Team: A journey to the planets

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[6]GFZ - Potsdam, Geomagnetism, Potsdam, Germany

The project "Bimbim's Team: A Journey to the Planets" was awarded by Europlanet with the main goal to awaken children's curiosity for planetary sciences. Science outreach to children is a major challenge for professionals in any field, especially because of the complexity involved. Initiating children into scientific subjects is not a trivial task. In his project, we tackle the challenge of reaching as many children as possible, combining science and art in an innovative strategy. "Bimbim's team" are puppets theater characters which have the power to fascinate children and transmit science in an unconventional way. Short movies were produced with three stories about the planets: general overview of all solar system planets, Earth and Mars.The videos come with illustrations and animations to better express the scientific content. They were recorded in three languages (Portuguese, English and French) in hopes of reaching an international scale. We expectthat these stories will also call the attention of schools and parents to bring science closer to their children.Another outcome of the project is the involvement of female scientists and the possibility to attract more scientists, especially the minority groups.

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OGGM-Edu: an open-source educational platform about glaciers and glacier modelling

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OGGM-Edu (https://edu.oggm.org) is an educational platform about glaciers, with the main goal to provide tools and materials for instructors who want to teach about glaciers at secondary schools, in workshops or at universities. Interactive web applications and open access images provide materials for entry-level classes with no experience in physics or programming. Jupyter notebooks at various levels of complexity offer guidance to run and develop simple modeling experiments in the python programming language. OGGM-Edu follows a decentralized open source model: we encourage our users to mix and remix our templates, and offer technical help to develop new classes, run the notebooks on a dedicated cloud service, or translate our materials to various languages. With this contribution, we are looking to connect with educators and scientists in all fields of geosciences interested in online teaching resources.

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Earthquake education and training program at the school level in India

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India has experienced many large earthquakes since historical times, causing large-scale damage and the loss of many lives. More than 2/3rd of the country's total area is exposed to varying degrees of earthquake hazard. The ongoing efforts to advance earthquake science and research experiments have significantly improved our knowledge in recent years. However, we are still far from predicting them. Although some short-term forecasts have been successful, they are generally of limited practical use for earthquake disaster management. To achieve the ultimate goal of mitigating the earthquake hazard, it is essential to focus on systematic R&D efforts. At the same time, earthquake education, training, and knowledge dissemination are critical to minimizing the impact of an earthquake. In India, these aspects are being addressed through specific modules and programmes on a smaller scale. The School Earthquake Laboratory Program is one such module, initiated about two decades ago with a view to introduce basic earthquake education at the secondary school level, inculcate the culture of measurements and interactive learning, and create awareness amongst the students and public at large. The programme was initially implemented in the northwest and northeast Himalayan regions and extended to a few other regions later. The paper briefly presents a summary of efforts made so far and further steps required in this direction.

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Teaching on Disaster-Risk to diverse undergraduate careers: merging Science and socio-humanistic perspectives within a situated context and from vocational interests

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In Colombia, classified as a High Risk country in the INFORM Index for risk management developed by the European Commission, Geosciences contents at primary school levels are practically absent, and there are extremely few courses on Natural Hazards and Disaster Risk Reduction at undergraduate level. This fundamental gap results in a generalized lack of knowledge in Earth Systems, Socio-Geo-ecological systems and DRR frameworks, and ultimately limits local capacities in decision-making.

In order to reduce the lack of knowledge at undergraduate level, we re-designed the general course “Natural Hazards and Disasters” at Universidad de Los Andes to a student-centered virtual modality, open to all undergraduate programs of the university. At the end of the course, students from any background are expected to be able to analyze and explain the factors that condition natural hazards, and discuss the vision of disasters as social constructions. The course seeks to sensitize students about the role that we all have, from the different disciplines, both individually and collectively, to reduce diverse vulnerabilities, taking into account specific cultural contexts in Colombia. Students are grouped into disciplinary and multidisciplinary teams to address a case study and analyze it from each vulnerability perspective, according to their careers. The resulting study-case is later used to produce a podcast, which they discuss in a final forum.

Regular evaluation of the course in the last three years attests for improvement of developing abilities, targeting learning goals, rise awareness on Disaster Risk Reduction and motivate proposals on Nature-based and Community-based solutions.

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"School catchment" as educational and scientific base for the Sendai Framework, Nexus and 2030 Agenda

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The Sendai Framework, Nexus and 2030 Agenda should be supported by scientists and managers, but their real strategies need to be implemented at the citizen level. In this work, we illustrate the "school catchment" concept as a tool for practical actions based on citizen science and a better understanding of hydrological processes. As a case study, we established the Mampituba river "school catchment" (1940 km^2) in southern Brazil. The minimum requirement for a "school catchment" is the installation of flow- and rainfall-gauging stations to support science learning, discovery, and education at any level by engaging local citizens. We have conducted detailed hydrological monitoring and field survey especially at the upper region of the catchment where sediment-related disasters occur frequently. Besides publishing scientific papers, upon request, we have reported and explained the results to Geopark managers, city officials, mountain guides, and general residents. Such education activities have helped them deepen their understanding of the local hydro-environment. The citizen science promoted within this "school catchment" is making residents more aware of their environments, with a clear increase in interest in topics such as water- and sediment-related disasters, water-energy-food security and ecotourism. Implementing "school catchments" is one way of empowering local communities to find their appropriate behaviors towards sustainable development.

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JH06c - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

The marriage between Poetics and Aesthetics in audiovisual media for effective scientific communication

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A short documentary "The Grand Tour of the 21st century. Naples between art and technology " is presented here on the presentation of innovative technological results, obtained in a context of green energy resources exploitation (GeoGrid project, POR Campania, Italy, ERDF 2014-2020). The documentary was developed with an innovative artistic language that uses the poetic, participatory and performative modality belonging to documentary. This project stems by the fact that scientists are called upon to make an effort to involve and share crucial issues of research, allowing even non-experts to appreciate the results achieved in their work. On the other hand since art and science have always influenced each other, and both artistic experimentation and scientific dissemination share the need to involve the public in what is happening around us, we firmly believe that a mix of the two languages can become a powerful tool for scientific dissemination.

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Geoscience Connections

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"Geoscience Connections" is a project to connect the eight IUGG Associations through interviews with early-career scientists (ECS), secretary generals and presidents of each association. The main objective of this project is to transfer scientific knowledge to the general public by connecting a variety of scientific subjects from all IUGG associations. Science outreach movies have a great potential to attract the attention of the public, especially through social media. The project is interdisciplinary, diverse, international and inclusive.Short movies were produced especially with ECS to emphasize the importance of the great variety of topics related to IUGG and to encourage young students to pursue careers related to geodesy and geophysics. The interviews with the IUGG secretary generals and presidents will be filmed during the IUGG Assembly, where most of them will be present. The documentary containing these interviews will be published at the IUGG Social Media Channels until December, 2023. In this talk we will show how the interviews were designed and some examples of short movies with ECS.

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JH06c - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Content Creation from the IAGA Social Media Working Group

DOI: 10.57757/IUGG23-3427 - LINK

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In a world where all types of information are available online, science and its outreach also needs to expand. Content creation has become an important aspect of science communication and IAGA scientists are playing a major role in it. IAGA is one of the associations under IUGG which promotes the work of Earth and space scientists studying the magnetic and electrical properties of planets, interplanetary bodies, the Sun and their different phenomena. An outcome of the last IUGG meeting in 2019 was the formation of a dedicated IAGA social media working group to provide an easily accessible platform and an online community for IAGA members; to bridge the gap between scientists and the general public; to increase awareness of the varied work of IAGA; and to promote the work of early career researchers (ECRs) and under-represented groups in IAGA.

This abstract covers an overview of the work undertaken by this working group and content shared on our many different social media platforms - Twitter, Instagram, Facebook, LinkedIn, YouTube, and a blog. The blog posts cover a range of topics including PhD stories on academic life, updates from the community, and historical information. On our other platforms, we share our blog as well as job opportunities, upcoming conferences, workshops, outreach opportunities, new publications, and videos covering the work of IAGA. We hope to attract other members to the group by describing the idea behind our content creation and in turn take ideas from the community to improve our reach.

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JH06c - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Connecting the Latin America hydrology community around the 23 Unsolved Problems in Hydrology

DOI: 10.57757/IUGG23-4616 - LINK

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The 23 Unsolved Problems in Hydrology (23UPH) have been recently proposed to guide research efforts and invigorate the field. While this is a great example of community level effort to generate and consolidate important scientific questions, it is only natural that there are remaining biases regarding subfields of the discipline and non-representativeness of participants due to traveling limitations. Here, we present a practical study case of how enhanced digitization allowed our community to gather and synthesize recent research related to the 23 UPH from the Latin American perspective. This synthesis at the Latin American scale recognizes a community with shared water resources, cultures, and needs and offers to the broad international hydrological community a complementary set of unique regional processes and problems. The Latin American initiative was announced through mailing lists in August 2021, it attracted responses from several countries beyond Latin America. The first hybrid meeting in November 2021 counted with 27 in-person and 66 remote attendees. The aim was to form decentralized groups who would be able to: (1) synthesize past and current research for each of the 7 major UPH themes and (2) adapt and propose new UPH focused on Latin American peculiarities. Each subgroup had 2-4 leaders who were responsible to engage other specialists and propose virtual working session during 2022 which were later reported to the larger group. The community has finished the synthesis phase and is currently promoting a workshop to finish proposed questions from Latin America.

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JH06c - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Scientists for Ocean Literacy - Empowering scientists as ocean advocates in the UN Decade of Ocean Science for Sustainable Development

DOI: 10.57757/IUGG23-2401 - LINK

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[4]AZTI, Marine Research- Basque Research and Technology Alliance BRTA, Pasaia, Spain

Science alone cannot provide the solutions to the challenges we face - we need wider society to actively contribute. This has pushed forward the need for more ocean literacy. The Scientists for Ocean Literacy project of the UN Decade of Ocean Science for Sustainable Development 2021-2030 aims to empower scientists to actively engage with society and foster sustainable behaviour. The project expands the horizon of science communication towards a multi-stakeholder and multi-disciplinary dialogue, while building on the existing best practices of the European oceanographic and meteorological agencies.

Ocean literacy raises awareness about our connection with the ocean and promotes co-creation of solutions to environmental degradation. Scientists should be working hand in hand with other professionals, specialists, and educators in developing impactful ocean literacy activities. Furthermore, this would produce a fertile ground for co-creation among disciplines and sectors. Ocean literacy must be recognized as an important aspect of the work of research institutions and supported in scientific careers (Eparkhina et al, EuroGOOS, 2021).

Successfully implemented at pan-European level and with partners from the Atlantic, Mediterranean, and the Arctic regions, the EuroGOOS ocean literacy work has created new synergies and supported the efforts of UNESCO-IOC. A new addition to the Scientists for Ocean Literacy project is the establishment of the DOORS Ocean Literacy Network in 2023. The Network brings together academia, universities, NGOs, and communicators to promote the understanding of the scientific project results and foster ocean culture among the Black Sea citizens of all ages.

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JH06c - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

GGOS contribution to increase visibility of Geodesy and emphasize its value to science and society

DOI: 10.57757/IUGG23-0594 - LINK

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[4]*GSI Geospatial Information Authority, Geodetic Department, Tsukuba, Japan*

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) is a collaborative contribution of the global geodesy community to the observation and monitoring of the Earth System. Geodetic observation techniques and analysis infrastructures, as well as high-quality geodetic products, provide the basis for advances in Earth and planetary system sciences and for various applications.

One main objective of GGOS is to support activities and initiatives to communicate the value of Geodesy to science and society, as well as contribute to understand and solve complex issues facing the global geodetic community.

Towards this objective, GGOS has established and maintains a website **ggos.org**, which serves as a **point of entry to Geodesy** to facilitate discoverability and usability of geodetic data and products. This includes user-friendly and illustrative descriptions about geodetic observation techniques and results. GGOS has also recently produced short **videos to explain the value of Geodesy** to non-geodesists. The new "Discover GGOS and Geodesy" video is available in multiple languages (youtube.com/@iag-ggos).

Presently, GGOS is working on the implementation of a comprehensive geodetic portal, the **GGOS Portal** (ggos.org/portal), which should realize in future a comprehensive and descriptive source of geodetic information with detailed metadata. With this, GGOS engages with diverse user communities to increase awareness of Geodesy and the ever-expanding utility of Geodesy in everyday applications.

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JM03a - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Polar climate and weather station (PCWS): The next generation surface meteorology observing system for Antarctica

DOI: 10.57757/IUGG23-0647 - LINK

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[3]*University of Wisconsin-Madison, Space Science and Engineering Center, Madison, USA*

Observing the surface meteorology of Antarctica has been a valued contribution in our understanding of weather and climate behavior. With over forty years of automatic weather stations (AWS) across the continent, the electronic systems used to capture these observations has been evolving from in-house developed systems to commercial-off-the-shelf systems. Experiences in having the best available observations at an affordable price lead to seeking a new solution to meet as many needs of the future as possible while broadening participation. Over the last six years, effort has been put into the development of a new electronics core for acquiring weather and climate observations. This report will review the development and outcomes of the Polar Climate and Weather Station (PCWS) project. Students at a two-year technical college in concert with an established university broadened participation and exposure of Antarctica, Antarctic meteorology, and electronics to those who would otherwise not have had the opportunity. In addition to the advances, the challenges endured by this project will also be reviewed such as the unexpected pandemic and supply chain issues that followed hampering the project. The results of this effort have provided the basis for a future observing system for the benefit of all.

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JM03a - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

AMIGOS stations: Ice-ocean-atmosphere multi-sensor systems

DOI: 10.57757/IUGG23-3731 - LINK

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The Automated Meteorology - Ice - Geophysics - Ocean observing Systems are a series of multi-sensor stations that have been employed for in situ data gathering in support of polar research since 2009, with multiple installations on the Antarctic Peninsula, the Nansen Ice Shelf, and on Thwaites Glacier's eastern ice shelf. The station series have been optimized for weather data collection and near-surface glaciology (AMIGOS-I) and later augmented with sensors for measurements related to ice-ocean interaction and internal ice sheet temperature profiling (AMIGOS-II and -III). The stations are powered by a solar + battery system, and provide real-time data through an Iridium uplink. The stations include cameras, weather instruments, thermistors, and GPS sensors, with later versions including ocean instruments (CTDs and doppler current meters) and a Distributed Temperature Sensing (DTS) fiber optic system. We present an overview of the instrument, past data from earlier installations, and a summary of the data sets and results from the two AMIGOS-III units installed on the Thwaites Glacier ice shelf.

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JM03a - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Towards continuous measurements of snow drift and sublimation in polar environments

DOI: 10.57757/IUGG23-4561 - LINK

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[1]Ecole Polytechnique Fédérale de Lausanne- Valais, Laboratory of Cryospheric Sciences- CRYOS, Sion, Switzerland
[2]Ecole Polytechnique Fédérale de Lausanne, Laboratory of Cryospheric Sciences- CRYOS, Lausanne, Switzerland
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In polar regions, and specifically in continental Antarctica, the local surface mass and energy balances can be largely controlled by snow transport in form of drifting and blowing snow particles, and sublimation both from the snow or ice surface and from the airborne snow particles. Adverse conditions in such extreme environments make continuous and reliable measurements of snow drift and sublimation a challenge, especially during the period of polar night and in absence of maintenance. Additionally, existing state-of-the-art snow mass and moisture flux measurement systems have relatively large power requirements, often resulting in spurious values or data gaps due to insufficient power supply from the autonomous wind and solar based power systems. In this contribution, we present observations of drifting snow events and latent heat fluxes obtained from collocated installations of classical eddy covariance instrumentation, optical snow particle counters, and acoustic particle flux devices deployed in Queen Maud Land, East Antarctica. We investigate the coherence of the optical and low-power acoustic snow drift measurements and compare them to numerical simulations of mass fluxes at the sensor sites. Furthermore, to mitigate the problems of potential power failure, low-power, fast-response humidity sensors are tested in laboratory and field settings to obtain latent heat flux estimates at largely reduced power consumption in comparison to eddy covariance measurements using infra-red gas analysers. Promising or successful novel systems may be a viable alternative for recording continuous time series of sublimation, in particular in the polar night season, and at significantly lower cost.

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JM03a - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Connections between supercooled liquid water clouds, melting layer and precipitation phase transitions at the Antarctic Peninsula

DOI: 10.57757/IUGG23-4910 - LINK

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[2]*CIIMAR - Interdisciplinary Centre of Marine and Environmental Research of the University of Oporto, Coastal and ocean dynamics, Porto, Portugal*
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Co-existence of ice and liquid clouds plays an important role in the cloud life cycle, as well as in precipitation formation and radiative balance. According to satellite observations, coastal regions show the most important proportion of supercooled liquid water (SLW) content in mixed-phase clouds (20-60%), while in the interior this proportion decreases significantly, up to less than 10% in the high Antarctic Plateau (Listowski, et al., 2019). This study is based on two field campaigns on King George Island, northern Antarctic Peninsula, at Escudero station (Portuguese Polar Program projects TULIP/APMAR, February 2022) and King Sejong station (APMAR2 project, February 2023). We present the results of the measurements of SLW content using a new instrument, the universal water content (UWC) sensor, capable to measure both the total and supercooled liquid water content in clouds, by using two vibrating wires sensible to the liquid droplets. We combine the UWC measurements with vertical profiles of tropospheric clouds using a mini-pulse lidar (data provided via MPLnet network) and a vertically-pointing micro rain radar (MRR-2 at Escudero, and a higher vertical resolution MRR-Pro at King Sejong), radiosonde measurements and ERA5 reanalysis data to characterize the tropospheric thermodynamic structure, the melting layer and the precipitation phase transitions. During preliminary case studies, ERA5 specific liquid cloud content vertical profiles showed an agreement with the UWC sensor in the detection of liquid water layers below 2 km altitude, however ERA5 still presents problems to represent the presence of liquid layer clouds at higher altitudes.

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JM03a - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Autonomous measurements of atmospheric condensed water over East Antarctica in the framework of the AWACA Project

DOI: 10.57757/IUGG23-3541 - LINK

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[2]École Polytechnique Fédérale de Lausanne,
Environmental Remote Sensing Laboratory LTE, Lausanne, Switzerland
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[4]CEA, Laboratoire des Sciences du Climat et de l'Environnement LSCE, Saclay, France
[5]CNRS, Laboratoire Atmosphères- Observations Spatiales LATMOS - IPSL, Guyancourt, France
[6]CNRS, Laboratoire Atmosphères - Observations Spatiales LATMOS - IPSL, Guyancourt, France

In this era of global warming, the climate of the Antarctic continent is extensively studied with climate models, as even a small loss of its polar cap may have a big impact on global sea level rise. However, the meteorological observations needed to evaluate and calibrate models remain scarce, especially in the atmospheric column, in the winter season and away from any inhabited station.

For this purpose, the AWACA (Atmospheric WAter Cycle over Antarctica) project aims to deploy 3 autonomous OPUs (automated Observation Platform Units) sheltering radars and lidars working at various wavelengths along a transect from coastal Terre Adélie to Concordia station, 1100km from the coast to 3200m on the Plateau. These instruments will perform condensed water measurements throughout the lower tropospheric column to characterize clouds and precipitation. Water vapor and snowflakes isotopes measurements will also be made by a spectrometer.

The OPUs will operate during 3 years, being visited only once a year. They will be isolated from any station and therefore self-powered.

A description of the OPUs' design, and the challenges associated with their stand-alone deployment in a harsh and remote environment and the various measurements they will perform will be presented.

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JM03a - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

The future of the International Commission on Polar Meteorology (ICPM): Challenges and opportunities

DOI: 10.57757/IUGG23-0645 - LINK

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For over 60 years the International Commission on Polar Meteorology has been a part of the fabric of the international community, as illustrated in its active participation in IUGG and IAMAS meetings over the years and support for the Workshop on Antarctic Weather and Climate and Antarctic Gravity Wave Instruments Network. This presentation will assess the state of the Commission today with recent updates to it statutes and specifically with a look toward future activities. One of our primary targets for the future is to be more inclusive. This includes widening membership across a wider range of countries and engaging early career scientists. Elements include a balance in the commissions' science endorsement and sessions at biennial meetings across topics centered on the Arctic, the Antarctic, and the Third Pole of the Himalayan Mountains. Support for young scientists and students will be a cornerstone for the ICPM moving forward, along with recognition of early and mid-career efforts of polar meteorologists. These opportunities are in various stages of development, and there are or will be challenges along the way.

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JP01a - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Tidal Dynamics in the Whole Atmosphere Models Constrained by Meteorological Analyses

DOI: 10.57757/IUGG23-4708 - LINK

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Solar thermal tides in the Earth atmosphere play an important role in the dynamics, energetics and transport from the surface to the thermosphere-ionosphere region. Tidal dynamics and its variability impact the global and regional coupling between atmospheric layers. Paper will discuss main drivers and metrics of observed tidal variability in the Mesosphere and Lower Thermosphere (MLT) evaluating capability of whole atmosphere model predictions constrained by meteorological analyses below the stratopause to reproduce it. The observed influence of the data-constrained lower atmosphere on the MLT dynamics is well captured by simulations that are capable to predict the global and regional tidal variability deduced from the space-borne and ground-based measurements of temperature and winds. The model-model and model-data differences in the representation of tides and their effects will be highlighted and discussed. Along with the scale-aware formulations of dynamics-physics coupling in models to adequately constrain the diurnal cycles, daily mean prevailing flows, and wave-wave interactions the rapid (~1-hr cadence) analysis of MLT data will likely improve realism of tidal dynamics in the whole atmosphere predictions.

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How should storm surge barrier maintenance strategies be changed in light of inter-annual tidal cycles and sea-level rise?

DOI: 10.57757/IUGG23-0730 - LINK

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Sea-level rise, changes in storminess and population growth are increasing the risks of coastal flooding. The impacts are amplified in coastal cities due to the high concentration of inhabitants, infrastructure and services. Storm surge barriers can provide flood protection in these low-lying areas with long exposed coastlines. Maintenance is vital to ensure these complex and unique structures remain reliable and comply with legal protection standards. To ensure safe working conditions, water level thresholds above which maintenance work must stop are defined. This study evaluates the changes in past and future water levels exceeding the maintenance threshold to inform management, maintenance and operation strategies of storm surge barriers. The Maeslant barrier in the Netherlands is used as a case study. Results show that 13% of maintenance threshold exceedances occurred during the maintenance season. The effect of sea-level rise and natural inter-annual tidal cycles on future threshold exceedances is also assessed. Findings reveal that the maintenance window will shift earlier in the year and narrow until exceedances occur regularly all year-round. As sea-levels rise, tides play an increasingly dominant role in maintenance threshold exceedances, which in turn will significantly influence maintenance work. This analysis highlights that maintenance strategies at the Maeslant barrier need to be adapted for the barrier to remain operational until its design life of 2100. This analysis can be applied to other existing barriers to assess future intervention points and for barriers in the design phase to verify the implications of design decisions on planned maintenance

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JP01a - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

The accurate digitization of historical sea level records

DOI: 10.57757/IUGG23-1209 - LINK

Patrick Mcloughlin[1], Gerard McCarthy[1], Glenn Nolan[2], Rosemarie Lawlor[3], Kieran Hickey[4]
[1]Maynooth University, Geography, Maynooth, Ireland
[2]The Marine Institute, Oceanography, Galway, Ireland
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[4]University College Cork, Geography, Cork, Ireland

Knowledge of regional sea level variations is pivotal to understanding coastal vulnerability. Fundamental to understanding these is the availability of sea level data. In Ireland, existing long sea-level records are rare and are in the north and east of Ireland. Paper marigrams do exist in different locations but are not currently digitized.

Techniques of marigram record digitization are in flux with a number of different techniques in practice. While issues such as distortions in scanned marigrams may be briefly mentioned in literature, what is often not discussed in detail are the issues that arise when digitizing. Such issues as bends, skews, or variations in line thickness in the paper marigram can offset sea level values by a significant amount.

Here we use the case study of Dún Laoghaire (near Dublin) from 1925–1933. We digitize the original marigram trace plus a matrix of known values to assess for any offsets. By comparing the original digitized data and the adjusted data, we can improve our accuracy to the 1 cm level to accurately recover sea levels.

The technique uses freely available software and can be flexibly applied to a range of data thus offering the opportunity to unlock the data held within these sea level archives.

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JP01a - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Tidal turbulence in deep Mariana Trench waters?

DOI: 10.57757/IUGG23-0343 - LINK

Hans Van Haren[1]
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To study potential turbulent water motions near the deepest point on Earth in the Challenger Deep of the Mariana Trench, a 588-m long string equipped with specially designed sensitive temperature sensors was moored for nearly three years in 10.9 km water depth. Detailed analysis of one year of good data distinguishes ubiquitous 100-m tall internal waves and hundreds of meters slanted convection turbulent spurs due to internal waves breaking from above. The spurs can occur on a tidal periodicity. Furthermore, internal tidal wave breaking including 100-m tall turbulent overturns reaching the trench-floor is associated with warm water push from above. Once, such tidal wave breaking at the trench-floor occurred precisely during the passing of a tropical storm, which thus interacts directly with deep-trench motions possibly via barotropic sealevel variations. The different turbulence types prevent the hadal waters from being still, which is an important necessity for deep-trench life.

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JP01a - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Intensified internal tides in Explorer and Dangeard Canyons (Celtic Sea shelf edge) observed by a deep ocean glider

DOI: 10.57757/IUGG23-0731 - LINK

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Explorer and Dangeard Canyons are named limbs of the large, dendritic Whittard Canyon system that incises the Celtic Sea continental slope. The system is known to feature large (order 80-m amplitude) semidiurnal internal tides, assumed to be generated at the shelf break to the southwest and focused into some limbs of the canyon by its steep, converging bathymetry. Interestingly, other limbs of the same system are much less tidally energetic. These large, but spatially heterogeneous internal tides are thought to have a variety of environmental impacts, from benthic faunal distribution to triggering turbidity currents.

In summer 2022, a University of Washington DeepGlider was deployed in and around Whittard Canyon for 45 days. After correcting for the internal spring-neap cycle, the largest semidiurnal internal tides (order 120-m amplitude) were observed at the mouths of Explorer and Dangeard Canyons and in both limbs the vertical oscillation of isopycnals progressed up-canyon (at 0.6-1.9 m s^{-1} in Explorer and 2.0 m s^{-1} in Dangeard). The associated available potential energy was highest in the lower half of the water column and decreased up the limbs. Finally, a 13-hour yo-yo CTD/LADCP station at the mouth of Explorer Canyon, competed during a coincident habitat mapping and benthic ecosystem survey (JC237), showed the up-canyon energy flux to be 6.7 kW m^{-1}. This evidence suggests very high levels of internal tide dissipation and resulting turbulent mixing within these two canyon limbs, which are likely to have considerable impact on local benthic ecosystems, sedimentological processes, and biogeochemical cycling.

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Tidal loading stress in the Bay of Fundy and induced seismicity: A re-assessment

DOI: 10.57757/IUGG23-5002 - LINK

Pierre-Michel Rouleau[1]
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Loading of the Earth's surface by the large marine tides in the Bay of Fundy produces a periodic stress field that is an order of magnitude larger that the global-scale, body-tide stress field. Structurally, the Bay is underlain by rock formations, akin to fluid-filled, fractured media. The locally-distributed stress is conducive to the migration of excess pore-pressure into unstable faults. Recent studies on correlations between the tidal stress tensor and focal mechanisms inferred from earthquakes in tectonically active areas have underscored the role of ocean tide loading; this prompts the question whether tidally-induced excess pore-pressure can trigger earthquakes in the Bay of Fundy, even though the area is tectonically passive. Only Beaumont and Quinlan (1977) have addressed this question; however, over the nearly 50 years since, much advances have been achieved in every aspects of the oceanographic and geophysical dynamics of the Bay of Fundy, in parallel with work elsewhere on precisely mapping the displacement field of loaded coastal regions via GNSS data. In this re-assessment, I examine the loading contribution of the predominant tidal constituents, M_2 in particular, about which the Bay of Fundy (and Gulf of Maine) marine system resonates. In assessing the consequences of the regional tidal loading, attention is paid to the permeable nature of the system's water-rock interface. Moreover, any perturbations of the system's resonant frequency are examined, particularly in relation to the increase of the amplitude of the M_2 marine tides in the Bay/Gulf system observed over the past century.

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JP01b - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

A tentative picture of changes in the open-ocean M2 tide since 1992

DOI: 10.57757/IUGG23-1316 - LINK

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Secular changes in ocean tides have been documented at some coastal tide gauges. These are often very localized (from river dredging, changes in river discharge, harbor modifications, etc.), but in some cases a network of gauges has observed coherent changes, suggesting the possibility of real, but small, wide-scale changes in the ocean tide. The three-decade time series of satellite altimetry may be sufficiently long and sufficiently accurate to address the problem over the open ocean; recent work by Bij de Vaate et al. is encouraging. Satellite altimetry from the Topex/Poseidon, Jason, and Sentinel-6 series of satellites is here used to map linear rates in the M2 tide. Large-scale coherent signals are detected across much of the ocean, at about 0.1 mm/year, and even larger in a few locations, but the likelihood of significant systematic errors is high. As a complementary approach, we also use a high-resolution ocean general circulation model, run over the same time interval, and forced by realistic changes in ocean stratification and sea-level rise; the stratification changes are by far the more important. As with altimetry, the likelihood of systematic modeling errors is also high, but the two approaches yield a picture of M2 trends that are surprisingly consistent in places, especially in the Indian Ocean and parts of the Pacific. Further improvements are expected as stratification is better delineated and as certain errors in altimetry are suppressed. Tidally coherent errors in satellite orbits and in several corrections will be discussed, with possibility of improvement in several.

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JP01b - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Analysis of the tidal range changes across the United States

DOI: 10.57757/IUGG23-1967 - LINK

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Tides are a crucial factor in the development and characteristics of coastal zones, as well as human activity in these zones. They (i) regulate navigation into and out of ports, (ii) set national and international boundary lines, (iii) are an important factor in the vertical zoning of tidal ecosystems, and (iv) affect the severity and frequency of coastal flooding. As a result, understanding and predicting how tides have changed in the past and how they will change in the future is of utmost practical and scientific importance. Nineteen years ago, the last comprehensive assessment of mean tidal range (MTR) changes across the United States was completed by Flick et al. (2003). As part of the NASA Sea Level Change Team, we are currently updating and extending the assessment temporally to present day and spatially to 120 NOAA tide gauge records, each with 19 or more years of data. We assess the inter-annual to decadal variability, long-term trends, and spatial characteristics of the MTR. Large heterogeneous variability caused by complex coastlines, including numerous estuaries and barrier islands, is found in the tide gauge records. In an attempt to identify coherent large-scale oceanic changes in MTR, we first build coastal indices by grouping time-series with similar variability. Subsequently, these coastal indices are then used to separate more localized changes in individual MTR time-series. In this presentation, we will discuss a variety of case study examples providing an overview of how MTR has been changing spatially and temporally since the late 19th century.

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JP01b - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Impact of 18.61-Year Nodal Tidal Cycle on the Highest and Lowest Astronomical Tides along the Northwest Pacific Ocean Coast

DOI: 10.57757/IUGG23-3154 - LINK

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Taiwan Province of China
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State Key Laboratory of Geodesy and Earth's Dynamics- Innovation Academy for Precision Measurement Science and Technology, Wuhan, China

The lunar nodal cycle, causing by moon's declination variations over the period of 18.61 years, results in changes in the amplitude and phase lags of global tidal constituents. However, the observed range in tidal amplitude is at present not yet well understood, and it is crucial for coastal hazard planning and chart datum. The impact of the nodal tide including its plausibly varying amplitudes and phase changes on the highest astronomical tide along the Northwest Pacific coast in North American could be important as a scientific basis for future coastal disaster planning. Additionally, there is no standard procedure of computing the lowest 18.61-year astronomical tides. Hence, we analyzed the contributions of various factors for calculating the lowest astronomical tide, including time spans, sampling frequencies, number of tidal constituents, and nodal tide correction, and establish a standard procedure which was adopted in Taiwan. Finally, we use a modified two-step harmonic analysis procedure to re-evaluate the seasonality and slope variability of the major constitutes (M_2, S_2, K_2, and O_1) along the Pacific Northwest coast in North Ametrica, and analyze the difference between the observed nodal amplitudes and the values predicted by equilibrium tidal theory.

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JP01b - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Glacial Arctic Tides and their Feedback to the North Atlantic

DOI: 10.57757/IUGG23-1702 - LINK

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The evolution of paleo tides has important implications for several branches of geoscientific research. For example, the presumably boosted generation of internal tides under glacial conditions is linked to increased tidal mixing, the intensity of the overturning circulation (e.g., Wilmes et al., 2019), and thus paleoclimate. Another application is the interpretation of Sea Level Index Points, influenced by the dynamic tidal levels, for reconstructing paleo sea level. A curious aspect, first predicted by Griffiths et al. (2008), is the emergence of a megatidal regime in the Arctic, with possible links to Heinrich Events (e.g., Velay-Vitow et al. 2020). While several studies reproduced the phenomenon, its extent, and sensitivity could be better constrained. Many ocean tide models operate with open boundary conditions in the Arctic, for which reason they suppress the free formation of the described tidal regime. Thus, it must be determined if this localized Arctic phenomenon induces significant feedback on tidal dynamics in the North Atlantic.

This contribution focuses on the emergence and robustness of the 'Arctic Megatide'. We present sensitivity experiments performed with a truly-global, data-unconstrained ocean tide model. The simulations establish the reproducibility of the phenomenon but predict high sensitivity to the representation of Self-Attraction and Loading (SAL), along with paleo bathymetric features. The ensemble is augmented with hybrid simulations, where the Arctic bathymetry is kept at a non-resonant state. The model differences indicate that the Arctic mega tide increases tidal mixing in the North Atlantic by 20%, with possible implications for ocean circulation.

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JP01b - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Polar ocean tides revisited

DOI: 10.57757/IUGG23-2136 - LINK

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Polar oceans have generally been harder to determine from satellite altimetry because the regions outside the 66 parallel has traditionally only been surveyed satellites in sun-sun-synchronous orbits. With Cryosat-2 this has changed. However, the satellite poses a number of challenges to tidal analysis because of its long ground-track repeat period (368 days) and its diverse measurement modes, low-rate mode (LRM) over the ocean and synthetic aperture radar interferometric mode (SARin) over ice surfaces and parts of the ocean.

The SAMOSA+ physical retracker was developed to process the Cryosat-2 data across measurement modes and hereby enables the determination of the sea state bias. This way it provides more stable sea level estimates compared with traditional empirical retrackers used in the Polar Ocean. Nearly 10 years of Cryosat-2 data have been analyzed for residual ocean tides to the FES2014 ocean tide model in the Arctic Ocean and Antarctic Ocean using the response formalism. We use data from the near monthly repeat pattern of C2 as this has a favorable alias period for most major constituents. Using this information, the long wavelength corrections to the major astronomical constituents M2, S2, K2, N2, K1, O1, P1, and Q1 tides have been mapped for both the ocean and floating ice shelves domains. In addition, several smaller third, fourth and sixth diurnal tides have been determined. Some of these small compound/over tides does show small but consistent signal across regions like the Weddell sea (South Atlantic) and in the Baffin Bay between Greenland and Canada.

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JP04a - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Progress in Representing Ocean-Ice Sheet Interactions in ECCO Ocean State Estimates

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[3]*UT Austin, Odin Institute, Austin, USA*

The "Estimating the Circulation and Climate of the Ocean" (ECCO) Consortium has a 20-year legacy of supporting fundamental climate research through the sustained production of innovative, global multi-decadal geophysical ocean state estimates. ECCO estimates are free-running solutions to state-of-the-art numerical general circulation models that are constrained with diverse, heterogenous, and sparse satellite and in-situ measurements in a least-squares sense.

In recent years the ECCO project has sought to better represent the drivers of global and regional sea level rise, including the contributions from ocean-driven melting of the Greenland and Antarctic Ice Sheets. This talk describes some of the challenges and benefits of expanding the scope of ECCO's original "ocean-only" state estimation system to include useful representations of ocean/cryosphere interaction in general and ocean/ice-sheet interaction in particular.

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JP04a - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Coupling the freshwater feedback into EC-Earth using the ice sheet model BISICLES

DOI: 10.57757/IUGG23-4381 - [LINK]

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Recent observations show that the Antarctic ice sheet is losing mass at an accelerating pace and that this is projected to accelerate in the coming decades, contributing significantly to sea level rise. Ice sheet contributions to sea level rise remains one of the largest sources of uncertainty to future projections. However, so far ice sheets are not included in the majority of climate models used in CMIP5/CMIP6 to make sea level projections. Therefore, to accurately simulate future climate and sea level rise, ice sheet models need to be included in Earth System Models.

Here, ocean temperatures from EC-Earth with CMIP6 forcing are used to calculate basal melt forcing for BISICLES. Ocean temperatures are averaged over five oceanic sectors of Antarctica and three different depth ranges. Then, a quadratic basal melt parameterisation calibrated on sea level contribution derived from observation-based changes in grounding line ice discharge is applied as forcing for BISICLES. Based on this methodology, freshwater feedback was then coupled asynchronously into EC-Earth at one-year intervals. We find that the choice of calibration and ocean temperature depth range significantly impacts the basal melt calculation and additionally show initial results from the freshwater feedback coupling.

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Buoyancy-driven flow of the Antarctic slope undercurrent and heat transport toward Amundsen Sea ice shelves

DOI: 10.57757/IUGG23-3035 - LINK

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[2]University of Southampton, Ocean and Earth Science, Southampton, United Kingdom

Elevated ice shelf melt rates in the Amundsen Sea have been attributed to transport of warm Circumpolar Deep Water onto the continental shelf via bathymetric troughs. These inflows are supplied by an eastward, subsurface slope current that opposes the westward momentum input from local winds and tides, referred to as the Antarctic slope undercurrent. Previous studies have linked variations in the melt rates of the Amundsen Sea ice shelves to wind fluctuations. Yet the mechanism via which the undercurrent forms, and thus what controls the mean shoreward heat transport, remains unclear. In this study we investigate the dynamics of the undercurrent using a high-resolution ocean-sea ice process model coupled to a static ice shelf. We explore the sensitivities of the undercurrent strength, shoreward heat transport, and ice shelf melt rates to winds, tides, diapycnal mixing, and geometry. We find that the undercurrent forms with realistic strength provided that there is a trough allowing access to the continental shelf and ice shelf cavity, and that there is a cross-slope buoyancy gradient. The vorticity balance within the CDW layer reveals that the bathymetric steering of the undercurrent toward the ice shelf is related to diapycnal upwelling that occurs as CDW melts the ice. These findings imply that the mean flow of the Antarctic slope undercurrent is primarily established by buoyancy forcing on the continental shelf, and motivate a focus on processes that influence cross-shelf/slope buoyancy gradients to better understand future changes in shoreward heat transport.

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Baroclinic ocean response to climate forcing regulates decadal variability of ice-shelf melting in the Amundsen Sea

DOI: 10.57757/IUGG23-0161 - LINK

Alessandro Silvano[1], Paul Holland[2], Kaitlin Naughten[2], Oana Dragomir[1], Pierre Dutrieux[2], Adrian Jenkins[3], Yidongfang Si[4], Andrew Stewart[4], Beatriz Peña Molino[5], Gregor Janzing[2], Tiago Dotto[6], Alberto Naveira Garabato[1]
[1]University of Southampton, School of Ocean and Earth Science, Southampton, United Kingdom
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[3]Northumbria University, Department of Geography and Environmental Sciences, Newcastle upon Tyne, United Kingdom
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[5]CSIRO, Oceans & Atmosphere, Hobart, Australia
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Warm ocean waters drive rapid ice-shelf melting in the Amundsen Sea. The ocean heat transport toward the ice shelves is associated with the Amundsen Undercurrent, a near-bottom current that flows eastward along the shelf break and transports warm waters onto the continental shelf via troughs. Here we use a regional ice-ocean model to show that, on decadal time scales, the undercurrent's variability is baroclinic (depth-dependent). Decadal ocean surface cooling in the tropical Pacific results in cyclonic wind anomalies over the Amundsen Sea. These wind anomalies drive a westward perturbation of the shelf-break surface flow and an eastward anomaly (strengthening) of the undercurrent, leading to increased ice-shelf melting. This contrasts with shorter time scales, for which surface current and undercurrent covary, a barotropic (depth-independent) behavior previously assumed to apply at all time scales. This suggests that interior ocean processes mediate the decadal ice-shelf response in the Amundsen Sea to climate forcing.

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JP04a - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Sensitivity of simulated water mass transformation on the Antarctic shelf to tides, topography and model resolution

DOI: 10.57757/IUGG23-2687 - LINK

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[2]University of Tasmania,
Australian Antarctic Program Partnership- Institute for Marine and Antarctic Studies, Hobart, Australia
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Water mass transformation (WMT) around the Antarctic margin controls Antarctica Bottom Water formation and the abyssal limb of the global meridional overturning circulation, besides mediating ocean-ice shelf exchange, ice sheet stability and its contribution to sea level rise. However, the mechanisms controlling the rate of WMT in the Antarctic shelf are poorly understood due to the lack of observations and the inability of climate models to simulate those mechanisms, particularly beneath the floating ice shelves. We used a circum-Antarctic ocean-ice shelf model to assess the contribution of surface fluxes, mixing, and ocean-ice shelf interaction to the WMT on the continental shelf. The salt budget dominates the WMT rates, with the basal melt of ice shelves driving buoyancy gain at lighter density classes and salt input at coastal polynyas driving buoyancy loss at heavier densities. We found a considerable sensitivity of the WMT rates to model horizontal resolution, tides and topography within the Filchner-Ronne, East and West Antarctica ice shelf cavities. In the Filchner-Ronne Ice Shelf, an anticyclonic circulation in front of the Ronne Depression regulates the rates of basal melting/refreezing and WMT and is substantially affected by tides and model resolution. Model resolution is also found to affect the Antarctic Slope Current in both East and West Antarctica, impacting the on-shelf heat delivery, basal melt and WMT. These results highlight the importance of resolving tides and small-scale features of the flow and topography to adequately represent water mass transformations on the shelf that directly influence the abyssal global overturning circulation.

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JP04b - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

From the large-scale ocean to the glacier margins: What controls the ocean temperature in SE Greenland's glacial fjords?

DOI: 10.57757/IUGG23-3128 - LINK

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Increased ocean-driven melting of Greenland's marine terminating glaciers is identified as a trigger of glacier retreat and dynamic ice loss from the ice sheet over the last few decades. The increasing melt rates, in turn, have been loosely attributed to a warming of the North Atlantic's subpolar gyre during a negative phase of the North Atlantic Oscillation (NAO). Limited data records from the fjords, however, mean that this hypothesis is largely untested. Here we use a 12 year record of properties from Sermilik Fjord, SE Greenland, and the nearby shelf, combined with historical ocean and atmosphere, and remote sensing data, to show that property changes inside the fjord are not simply related to the heat content of the North Atlantic's subpolar gyre or the NAO phase. Instead, we show that fjord properties are directly related to properties on the nearby continental shelf which, in turn, vary as a result of the regional wind-stress and export from the Arctic Ocean. The implication of these findings for reconstructing the variability of melt rates at the glaciers' margins back in time will be discussed.

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JP04b - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Sensitivities of the Energetics of the West Greenland Current to Greenland Ice Sheet Meltwater in Mesoscale Ocean/Sea-ice Simulations

DOI: 10.57757/IUGG23-4435 - [LINK](#)

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Meltwater from the Greenland Ice Sheet has the potential to freshen the surface of the Labrador Sea and limit deep convection. Typically, meltwater is added to ocean models at the surface, neglecting the observed mixing of meltwater within fjords. We investigate how a more realistic representation of meltwater amplifies the transport of freshwater across the southwest Greenland shelf break. Results from four coupled ocean/sea-ice simulations forced with atmospheric reanalysis are compared for the years 1992-1993. We compare eddy permitting and mesoscale eddy resolving (horizontal resolutions of approx. 5km and 3km in the study region, respectively) simulations with no meltwater to examine the importance of mesoscale processes in off shelf transport. Two different meltwater forcing schemes are implemented in the mesoscale eddy resolving configuration: meltwater added to the surface layer and meltwater vertically distributed over the upper 200m. When meltwater is added, there is an increase in off shelf freshwater transport (S_{ref}=34.7) compared to the no-meltwater case (total transport of 45.2 ~mSv). Transport off the shelf increases by 12mSv in the surface meltwater case and by 23.1mSv in the vertically distributed meltwater case. In the mesoscale eddy resolving simulations, when meltwater is vertically distributed, there is enhanced baroclinic conversion at the shelf break compared to the simulation with no meltwater. This suggests that meltwater from the Greenland Ice Sheet could have a disproportionate impact on freshwater transport into the Labrador Sea by modifying cross shelf exchange.

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Evolution of ice shelves in North Greenland during the last 30 years

DOI: 10.57757/IUGG23-0085 - LINK

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In north Greenland, which holds more than 2.7 m of sea level equivalent, the ice flows through ice shelves, as in Antarctica. These floating platforms are the most vulnerable parts of the ice sheets as the advection of warm, salty ocean waters increases basal melting, which can trigger an increase in ice flow into the ocean. Here we study the recent dynamic and geometric changes of all present and former ice shelves along the north coast of Greenland. We document the evolution of the surface elevation using data from the GIMP project, from NASA's instruments (ICESat-1/2, ATM, LVIS, GLISTIN-A) and generate DEMs using ASTER imagery between 2000-present. We also monitor changes in surface ice velocity and grounding zone evolution using a combination of optical and radar data. We use the elevation time series to monitor the temporal evolution of the ice shelves volumes and combine them with the surface flow velocity to calculate basal melt rates in a Lagrangian framework at unprecedented level of resolution. Finally, we compare our observations with nearby CTD measurements, the TOPAZ4b reanalysis of Arctic ocean physics provided by Copernicus Marine Service and model outputs from the Modèle Atmosphérique Régoinal. We show that basal melting, grounding line retreat and fracturing are rapidly increasing and is followed by an increase in ice discharge into the ocean. These observations demonstrate that significant changes are occuring in a region that has long been considered stable, which may have dramatic consequences for the ice sheet contribution to sea level rise.

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JP04b - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Calving of the Greenland Ice Sheet since 1985

DOI: 10.57757/IUGG23-2109 - LINK

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The Greenland Ice Sheet has undergone rapid changes in recent decades, as the ice has grown thinner and outlet glaciers have retreated bit-by-bit. Calving-front retreat often represents a response to environmental forcing, but at the same time, the slow etching away of ice can weaken the ice sheet and induce further glacial change. To better understand the causes and effects of recent changes in Greenland, we combine satellite observations of glacier terminus positions with a simple flow model to create a continuous, ice-sheet-wide history of Greenland's areal extents since 1985. With nearly four decades of monthly ice outlines, we explore the complex relationships between secular change and seasonal cycles of calving in Greenland, and we report on the mass changes associated with the ongoing advance and retreat of the ice sheet.

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration's Cryosphere Science Program.

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Internal waves generated by subglacial discharge: Implications for tidewater glacier melt

DOI: 10.57757/IUGG23-1130 - LINK

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[1]Oregon State University, College of Earth- Ocean- and Atmospheric Sciences, Corvallis, USA
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The ocean influences on mass loss at tidewater glaciers are poorly understood, leading to uncertainty in sea level rise projections. Subglacial discharge plumes drive mass loss via submarine melting and may also facilitate mass loss by modulating calving rates. However, current theories underpredict submarine melt rates at terminus regions that are far from discharge plumes, suggesting that they may miss key ocean processes. A new set of observations from autonomously deployed moorings less than 100 m from the terminus of LeConte Glacier, Alaska, and a high-resolution numerical model, reveal that the near-glacier ocean is filled with energetic internal waves. We find that the internal wave kinetic energy and frequency are correlated with subglacial discharge fluxes on weekly to seasonal timescales. The waves radiate away from the discharge plume and could enhance ice-ocean boundary layer fluxes of heat and salt along the terminus. Accounting for waves within current submarine melt rate parameterizations increases predicted melt rates by up to 70%. Because the dynamical ingredients - a buoyant plume rising through a stratified ocean - are common to many tidewater glacier systems, such internal waves are likely to be widespread.

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JP04c - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Broad spatial and temporal scales modulating ice/ocean interactions, an observational perspective

DOI: 10.57757/IUGG23-0655 - LINK

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In Antarctica and Greenland, interactions between Oceans and Ice sheets are crucial to the regulation of the global overturning circulation, the current acceleration of ice flow into the ocean and the associated global sea-level rise. Over recent decades, satellite, airborne and in situ ocean and ice observations have demonstrated with increasing temporal and spatial resolution that these interactions are complex and occur on a broad ranges of multidimensional scales. Using an observational lens limited to the past 30 years during which capabilities for direct observations have grown exponentially, I will present an overview of the complexity of the coupled system and the feedbacks involved, covering boundary layer, meso- and large-scale processes in the ocean, and the dynamical and geometric response of the ice at tens of meters to hundreds of kilometers scales. The advent of an array of remote and autonomous in situ technologies provide exciting perspectives for future fruitful explorations.

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Interannual variation of modified Circumpolar Deep Water volume in the Dotson-Getz Trough, West Antarctica

DOI: 10.57757/IUGG23-0761 - LINK

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In recent decades, wide-spread thinning of ice shelves in the Amundsen Sea has been recorded driven by basal melting. Relatively warm modified Circumpolar Deep Water (mCDW) flows onto the continental shelf and fills the Dotson-Getz Trough (DGT) and reaches the base of the Dotson Ice Shelf (DIS). Long-term hydrographic data (2007–2018) for the DGT were obtained during seven oceanographic surveys to study the interannual variation in mCDW volume and properties in the DGT and their causes. Although the mCDW volume showed relatively weak interannual variations at the entrance of the DGT, these variations intensified in front of the DIS. There, the mCDW volume was ~8 × 10^3 km^3 in 2007, rapidly decreased to 4.7 × 10^3 km^3 in 2014 before rebounding to 7.3 × 10^3 km^3 in 2018. Such interannual variability appears to result from local Ekman pumping along the DGT, with the dominant south-southeast wind modulating the amplitude of Ekman upwelling along the eastern boundary of the Amundsen Sea polynya during the austral summers of the surveyed years. We note a strong correlation between the wind variability and the longitudinal location of the Amundsen Sea Low.

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JP04c - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Temporal variability of meltwater in front of Dotson Ice Shelf

DOI: 10.57757/IUGG23-2323 - LINK

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[2]University of Gothenberg, Department of Marine Sciences, Gothenberg, Sweden

Ice shelves terminating towards the Amundsen Sea are losing mass rapidly, exporting an increasing amount of meltwater into the ocean. Investigation into the fate of the glacial meltwater in the Amundsen Sea is therefore pressing for predicting the future climate response to the ice shelf processes. However, observations near ice shelves often lack continuity in either time or space, limiting our knowledge of the meltwater pathway. In summer 2022, we deployed six ocean gliders in front of the Dotson Ice Shelf (DIS), obtaining two ship CTD transects and 573 glider profiles, yielding more than ten fine-resolution (median horizontal sampling interval: 650 m) glider transects along the DIS within three weeks, allowing us to compare the full picture along DIS over short time scales (median sampling interval: 4.5 days). Glider transects reveal that the meltwater content is higher (about 20 g/kg) in the west (outflow) and lower in the east (inflow), with a meltwater-poor layer centred at about 350 m sandwiched by two meltwater-rich layers (above about 250 m and centred at about 450 m). We find particularly meltwater-poor cores within the meltwater-poor layer, potentially indicating eddies. Isopycnals diverge near the meltwater outflow core and shoal below about 600 m at the inflow region, indicating geostrophic flow out of and into the cavity respectively. We calculate the volume transport of meltwater exported from the ice shelf cavity and assess its variability during the three weeks.

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Graph analysis for subglacial hydrology and sediment flux to the ocean

DOI: 10.57757/IUGG23-1515 - LINK

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A better knowledge of sediment flux to the ocean has many implications for understanding past and future cryosphere evolution including understanding potential impacts on ice shelf stability and ocean circulation, understanding the record of past cryosphere events from sediment records and understanding impacts on nutrient supply and CO_2 drawdown. Physical model studies of subglacial sediment transport are relatively few, and due to computational expense, these often do not explore the broader model space for the glacial scenario of interest. The lack of a comprehensive quantitative knowledge of the subglacial sediment transport system limits our ability to understand sedimentary records of ice sheet change, and to express the potential impacts of future cryosphere change on the ocean. I present here a graph analysis approach to enable broad exploration of model space to understand hydrological change and for quantitative estimates of water and sediment fluxes through the system and to the ocean. The analysis is based on the outputs of physical models, including an ice sheet model output and a subglacial hydrology model output. The analysis defines catchment-scale graphs of the subglacial hydrology network, from which subgraphs are defined optimised to the problem at hand. Such representations greatly reduce the model size and allow efficient development of an ensemble result. These subgraphs may be defined from prior information, or ad-hoc during run-time based on stochastic, probabilistic or adaptive algorithms. I demonstrate the approach for a synthetic example and show examples from catchment-scale model studies in Greenland and Antarctica.

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JP04c - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Hydraulic suppression of basal glacier melt in sill fjords

DOI: 10.57757/IUGG23-3027 - LINK

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We examine how hydraulically-controlled exchange flows in silled fjords affect the relationship between basal glacier melt and features of warm intermediate Atlantic Water (AW) outside the fjords. Using theory and an ocean-circulation model, we show that an exchange flow can be forced to transit into a hydraulic regime if the AW interface height decreases, the AW temperature increases, or the production of glacially modified water is boosted by subglacial discharge. In the hydraulic regime, the heat transport across the sill becomes a rate limiting factor for the basal melt, which is suppressed. An interplay between processes near the ice--ocean boundary and the hydraulically-controlled exchange flow determines the melt dynamics, and the sensitivity of the basal melt to changes of the AW temperature is reduced. The model results are discussed in relation to observations from Ryder, Petermann, and 79°N glaciers in North Greenland. We also outline how hydraulic suppression of basal melt can be represented in ice sheet modelling.

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JP04d - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Observations of the modulation of ice shelf basal melt rates by mesoscale oceanographic features

DOI: 10.57757/IUGG23-3054 - LINK

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We report on observations from instruments deployed on a pair of moorings sited ~5 km apart, beneath Ronne Ice Shelf, Antarctica. Measurements of temperature, salinity and current velocities for the period from early 2015 to mid-2019 demonstrate strong variability at timescales from tidal to interannual. Here we focus on features that are a few days in length that we interpret as vortices streaming past the site. The intensity of the vortices is enhanced towards the ice-shelf base; they are in geostrophic equilibrium, have a radius (12 km), substantially larger than the estimated internal radius of deformation (~1500 m) and have a relative vorticity that is 30 to 40% of the local planetary vorticity. The velocity of the features, determined by correlating observations from instruments on the two moorings, is the same as that of the ambient water flow. The time series of basal melt rates, measured using a collocated downward-looking radar, shows the melt rate signal to be dominated by an approximate spring-neap variability, but with a significant response to the eddying flow. Although tidal activity clearly affects basal melt rates, as illustrated by the strong ~14-day variation, the net effect of the vortices is less obvious. Here we argue that the cyclonic and anticyclonic vortices ventilate the thermocline via Ekman pumping, thus increasing melting. Such eddy features are clearly a significant component of sub-ice shelf ocean variability, at least in the study area.

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JP04d - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

The importance of Atlantic Water pathways in understanding glacier discharge in Northwest Greenland

DOI: 10.57757/IUGG23-4453 - LINK

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Warming of deep Atlantic Water in recent decades has resulted in extensive retreat of marine terminating glaciers in Northwest Greenland, increasing their discharge, contributing significantly to sea level rise. We use data and numerical models to consider whether the pathways of deep Atlantic Water, through the complex system of canyons of Melville Bay, increased the vulnerability of glaciers over the observed ocean warming period. New observations of salinity and temperature of the ocean water and bathymetry from NASA's Ocean Melting Greenland mission, as well as Mankoff's discharge estimates are combined with FESOM ocean model results. We find that the pathways of Atlantic Water are crucial for understanding the increase in discharge of certain glaciers over the ocean warming period. More specifically, the vulnerability of a marine terminating glacier in Northwest Greenland to Atlantic Water depends on its latitudinal position, the location of the fjordal channel entrance along the Southern or Northern canyon head and whether the fjordal channel is deep enough to be a pathway for Baffin Bay Intermediate Water. The Upernavik N and C glaciers, which are in the most vulnerable position, contributed 10% to the total discharge change of Northwest Greenland. In addition, the glaciers that exhibited the largest normalised discharge change showed correspondence between their discharge estimates and the observed changes in fjord geometry during the retreat of the glacier calving front. Warming of deep Atlantic Water impacted the normalised discharge estimates, but the sensitivity to the fjord geometry also controlled large parts of the observed trends.

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JP04d - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Antarctic surface water intrusion triggering seasonal rapid basal melting of drygalski ice tongue, east Antarctica

DOI: 10.57757/IUGG23-1619 - LINK

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Antarctic glaciers are losing ice rapidly to the ocean through basal melting of ice shelves/tongues. To better predicate future sea level rise, it is urgent to detect the rapid basal melting of ice shelves/tongues as well as ocean's role in this process. In this study, basal melting of Drygalski Ice Tongue (DIT), the seaward extension of David Glacier in Northern Victoria Land, East Antarctica has been detected using a surface deployed Autonomous Phase-sensitive Radio-Echo-Sounder (ApRES). The ocean water changes adjacent to DIT front has been revealed using an ocean mooring. ApRES observation suggests a rapid basal melting > 10 m/a close to DIT front in February and mooring data shows a synchronous ocean warming in austral summer, indicating Antarctica Surface Water intrusion to the base of DIT. The mooring data has been used to simulate the basal melting of DIT front, which coincides with ApRES measurements. We conclude that rapid basal melting close to the tongue front was likely triggered by intrusion of Antarctica Surface Water in austral summer. Glacier-ocean interactions, such as glacier basal melting, can be detected from spaceborne, terrestrial and oceanic observations and are important processes to predict future sea level changes. To better understand the driving forces of glacier changes, multi-disciplinary observation and numerical modeling are required.

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JP04d - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

The grounding zone of the Ekström Ice Shelf, East Antarctica – Geophysical characterization using GNSS, seismology and magnetotellurics

DOI: 10.57757/IUGG23-0152 - LINK

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Antarctica's ice shelves are a highly critical component for the interlinkage between ice sheet and ocean. Their shape and evolution play an important role for the strength of ice mass loss, e.g. by amplification or weakening of the buttressing effect. Ocean tides are the most important direct forces acting on the ice shelves, inducing vertical and horizontal motion and deformation. In our study we investigate the effect of ocean tides on the Ekström Ice Shelf. The northward flow of the ice is mainly modulated by the tidal constituents at the ter-diurnal and quarter-diurnal bands, whereas the dominant vertical tides have a diurnal and semi-diurnal periodicity and amplitudes up to ten times larger than the ter- and quarter-diurnal tides. The causes of the higher frequency tidal modulations are still poorly understood. The area of the largest effect of the higher frequency tides is assumed to be the grounding zone of the ice streams feeding the ice shelf.

Here we present first results of geophysical experiments at the grounding zone of the Ekström Ice Shelf conducted in the field seasons 2021/2022 and 2022/2023. In 2021/2022 we setup GNSS and seismic stations to record vertical and horizontal motion of the ice as well as seismic events in order to gain insights into ice dynamics and ground properties. In season 2022/2023 GNSS and seismic station were dismantled, and the experiments were complemented by magnetotelluric measurements to image the sub-ice ocean-land transition and the crustal structure beneath the ice stream.

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JP05a - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Proposed advancements in tsunami detection, measurement and forecasting through the un decade of ocean science

DOI: 10.57757/IUGG23-5001 - LINK

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Under The UN Decade for Ocean Science, UNESCO/IOC has established the UN Ocean Decade Tsunami Program (ODTP). The purpose of the program is to establish a global framework from which significant gains in both operational tsunami science (instrumentation, analysis, forecasting, etc) and preparedness capacities can be realized. To guide this effort a Scientific Committee was established to, in part, identify aspirational goals in both of these areas with the intent of fundamentally advancing the state of the Global Tsunami Warning and Mitigation System over the course of the Decade. In this paper, these specific goals related to tsunami detection, measurement, and forecasting will be outlined along with the types of instrumentation and analysis strategies being considered to achieve them. As a primary objective of the ODTP is to elevate the capacities of all at-risk IOC member States, the ODTP has prioritized strategies that encourage the participation of all at-risk states, in a way that can be seamlessly combined to develop a global tsunami sensing and forecasting network far more advanced and capable that could otherwise be achieved with individual, independent actions.

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JP05a - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami Digital Twin – A new paradigm for tsunami disaster resilience

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The digital twin is now recognized as digital copies of the physical world's objects stored in digital(cyber) space and utilized to simulate the sequences and consequences of target phenomena. By incorporating the physical world's data into the digital twin, users can fully view the target through real-time feedback.

Given the importance of the digital twin, the authors propose "Tsunami Digital Twin (TDT)" as a new paradigm in tsunami science and engineering to enhance tsunami disaster resilience.

The components of TDT are the transformation from "Data" to "Information" by integrating sensing, monitoring, and simulation; "Interpretation" of data and information; "Inference" by using available data and information to draw conclusions and consequences and decide policies and responses for social resilience. The fusion of these components is the key to gaining knowledge and insight for optimal solutions in the physical world. The components to be covered are the following six research themes that will be presented in the tsunami session.

Theme 1: Real-time tsunami inundation modeling and forecast capability.

Theme 2: Dynamic exposure estimation and guidance to mobile devices and connected vehicles.

Theme 3: Application of machine learning to enhance real-time tsunami inundation forecast capabilities.

Theme 4: Machine learning-based damage/loss estimation methods.

Theme 5: Remote sensing data analysis for mapping.

Theme 6: Social sensing of cascading disaster processes in the tsunami-affected area.

The digital twin is now recognized as digital copies of the physical world's objects stored in digital(cyber) space and utilized to simulate the sequences and consequences of target phenomena. By incorporating the physical world's data into the digital twin, users can fully view the target through real-time feedback.

Given the importance of the digital twin, the authors propose "Tsunami Digital Twin (TDT)" as a new paradigm in tsunami science and engineering to enhance tsunami disaster resilience.

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JP05a - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Pathway to achieving 100% of tsunami at-risk communities are prepared and resilient to tsunamis by 2030

DOI: 10.57757/IUGG23-0348 - LINK

Christa Von Hillebrandt-Andrade[1], *Srinivas Kumar Tummala*[2], *Silvia Chacon-Barrantes*[3], *David Coetze*[4], *Harkunti P. Rahayu*[5], *Denis Chang Seng*[6], *Bernardo Aliaga*[6]
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In June 2021, UNESCO IOC approved the Ocean Decade Tsunami Programme (ODTP) in response to the call to action by the UN Ocean Decade of Ocean Science for Sustainable Development (2021-2030). The ODTP has two overarching goals: (1) develop the warning system's capability to issue actionable and timely forecasts for tsunamis from all identified sources for all communities at risk, and (2) 100% of communities at risk are prepared and resilient to tsunamis by 2030. In 2022, a Scientific Committee for ODTP was established to develop a 10-Year Research, Development and Implementation Plan to reach these two objectives. This presentation will focus on three of the four areas of the plan:

-Enhance tsunami risk assessments and research on technologies, so the countries know their expected vulnerability and threat (tsunami characteristics), and can identify and prioritize the at-risk communities.

-Ensure all National Tsunami Warning Centres have access to data, tools and communication platforms, protocols and training to timely and effectively warn coastal and maritime communities threatened by tsunamis and other coastal hazards that are integrated into a multi-hazard framework.

-Emphasize the importance of building tsunami resilient communities that are prepared and ready to respond through the UNESCO IOC Tsunami Ready Recognition Programme.

Tsunami Ready is a global, voluntary community-based effort approved in 2022. It has 12 indicators categorized into Assessment, Preparedness and Response, and thus addresses all of the three aforementioned areas of the Plan. The objectives will be achieved through involvement of stakeholders at all levels and attention on capacity development and governance.

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JP05a - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Spatial and temporal coverage of a cargo-ship GNSS network to detect tsunamis

DOI: 10.57757/IUGG23-3624 - LINK

Bruce Thomas[1], James Foster[1], Tasnîme Louartani[2], Jean Roger[3]
[1]University of Stuttgart, Institute of Geodesy GIS, Stuttgart, Germany
[2]ENSG-Geomatics, ENSG-Geomatics, Champs-sur-Marne, France
[3]GNS Science, Earth and Structure Processes, Lower Hutt, New Zealand

Recent tsunamis demonstrate the urgent need for more densely spaced observations and direct measurements from the oceans. Most of the existing observing capacity is located on land or close to the shore, and often sparse (seismic network, land-based GNSS, tide-gauges and DART array), limiting our ability to predict, detect and respond to tsunamis. We propose a network of ships with GNSS systems as a way to fill this geodetic observation gap in the ocean by tracking changes in sea-surface height, and detecting even small, ~10 cm amplitude tsunamis of different origins. One year of navigation data from the commercial shipping fleet is used to generate statistical coverage maps of large ships for different epochs in the Pacific region which are overlapped with regions source of tsunamis and impacted by tsunamis. Some first results describe what a cargo-ship network might experience in terms of tsunami travel time and tsunami predicted amplitudes based on several tsunami models calculated over the Pacific. They clearly demonstrate that commercial shipping lines provide an excellent temporal and spatial coverage of the ocean globally. A focus on different regions indicates that the highest density of ships is near coastlines, and testing different tsunami origins helps understand more precisely how this network could improve regional early warning. By exploring the geographic relationship between tsunami sources, travel times and amplitudes with the ships locations, the discussion seeks to determine the ability of a defined ship network to provide effective warnings for the communities at risk and improve hazard mitigations.

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JP05a - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Advances and challenges in the implementation of the UNESCO/LOC tsunami ready recognition programme in the pacific and caribbean region

DOI: 10.57757/IUGG23-0257 - LINK

Laura Kong[1], Christa von Hillebrandt-Andrade[2], Carolina Hincapie Cardenas[1], Stephanie Soto[2], Alison Brome[3], Bernardo Aliaga[4]
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[4]UNESCO/IOC, Tsunami Prgramme, Paris, France

In June 2022 the Intergovernmental Oceanographic Commission (IOC) of UNESCO established the Tsunami Ready Recognition Programme. It is modelled after the US TsunamiReady® Program established in 2001. To receive Tsunami Ready recognition, each community must meet 12 indicators that cover Assessment, Preparedness, and Response. The recognition is renewable every four years. The Tsunami Information Centres in each region (ITIC in the Pacific, CTIC in the Caribbean, IOTIC in the Indian Ocean and NEAMTIC in the Mediterranean and Northeast Atlantic) facilitate the implementation of this Programme. To date, more than 30 communities in 20 countries in the Pacific and Caribbean, and 40 globally have been recognized.

ITIC and its Caribbean Office (previously known as the Caribbean Tsunami Warning Program) have been supporting the program in its different phases since 2012. In 2014, Anguilla, a UK Territory in the Caribbean, was the first to be recognized. Currently, with funding from USAID, ITIC, in coordination with CTIC for the Caribbean, is leading TR projects in several SIDS in the Caribbean and Pacific. It is also providing support through capacity development and sharing of best practices worldwide. Additionally, ITIC hosts the website for the Programme (tsunamiready.org). By conducting this work ITIC and CTIC and the countries, communities and other stakeholders will be contributing to the IOC Ocean Decade Tsunami Programme and specifically the goal of 100% of communities at risk are prepared and resilient to tsunamis by 2030. An overview on the implementation process, deliverables and challenges will be presented.

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JP05a - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Providing data, data products, software, and services for tsunami risk

DOI: 10.57757/IUGG23-3952 - LINK

Fatemeh Jalayer[1], *Hossein Ebrahimian*[2], *Konstantinos Trevlopoulos*[2]
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[2]*University of Naples Federico II, Structures for Engineering and Architecture, Naples, Italy*

Excellent science is enabled and enriched through making the relevant scientific research tools and results directly accessible to the scientific communities and the civil societies. The European Tsunami Risk Service (ETRiS) aims to collect, harmonize and make available tsunami risk related data (e.g., impact, damage, consequences), data products (e.g., fragility and vulnerability curves), software, and services in a way that they are findable, accessible, interoperable, and reusable by a broad user base. ETRiS is part of the candidate Thematic Core Service for tsunami (http://tsunamidata.org) and is integrated into the Data Portal of the European Plate Observing System (EPOS, https://www.ics-c.epos-eu.org).

This web platform (https://eurotsunamirisk.org) provides data products and services required for probabilistic tsunami risk analysis (PTRA) in a multi-risk context. Here are some features:

- Maps: visualizing data products and data sets
- Data Products: damage scales, fragility curves, consequence models, vulnerability curves
- Tsunami Impact and Consequence Datasets: selected raw/processed datasets of impact and damage incurred by tsunami
- Tsunami Risk Modeller's Toolkit: software and tools for tsunami risk analysis, stand-alone software and tools for post-processing raw data, model testing and validation
- E-Learning: Online teaching material, Jupiter notebooks, docker applications for probabilistic analysis and uncertainty characterization and propagation, fragility and vulnerability modelling, model testing and selection
- User support and organization of user testing and feedback workshops.

We herein present this service and its features and solicit input and collaborations for enriching it and widening its scope.

This work is supported by Horizon Europe Project Geo-INQUIRE. Geo-INQUIRE is funded by the European Commission under project no. 101058518 within the HORIZON-INFRA-2021-SERV-01 call.

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JP05b - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Accelerating global science in probabilistic hazard and risk analysis

DOI: 10.57757/IUGG23-3258 - LINK

Jörn Behrens[1], *Serge Guillas*[2], *Stefano Lorito*[3], *Finn Løvholt*[4], *Shane Murphy*[5], *Jorge Macías*[6], *Ceren Özer Sözdinler*[7], *Irina Rafliana*[8], *Simone Rödder*[9], *Dimitra Salmanidou*[10], *Jacopo Selva*[11], *Mathilde Sørensen*[12]

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[2] *University College London, Department of Statistical Science, London, United Kingdom*
[3] *Istituto Nazionale di Geofisica e Vulcanologia, Sismologia e Tettonofisica, Rome, Italy*
[4] *NGI, Computational Geomechanics CGM, Oslo, Norway*
[5] *IFREMER, Aleas Marins, Brest, France*
[6] *Universidad de Málaga, Departamento de Análisis Matemático, Málaga, Spain*
[7] *Gebze Technical University, Department of Civil Engineering, Gebze-Kocaeli, Turkey*
[8] *German Institute of Development and Sustainability IDOS, Inter- and Transnational Cooperation, Bonn, Germany*
[9] *Universität Hamburg, Sozialwissenschaften, Hamburg, Germany*
[10] *University College London, Institutional Research Information Service, London, United Kingdom*
[11] *University of Naples- Federico II, Dept. of Earth- Environmental- and Resources Sciences, Naples, Italy*
[12] *University of Bergen, Dept. of Earth Science, Bergen, Norway*

Probabilistic Tsunami Hazard and Risk Analysis (PTHA/PTRA) has its roots in the corresponding probabilistic approaches in the seismic sciences. However, there are several substantial differences in the cascading source and effect modeling chain, necessitating for complex workflows, involving still larger gaps in data and knowledge, and requiring different approaches in dealing with uncertainties.

The European Cooperation in Science and Technology (COST) Action AGITHAR (Accelerating Global Science in Probabilistic Hazard and Risk Analysis) has run for four years and has since then gathered parts of the scientific community around PTHA/PTRA and made some substantial progress in communicating and unifying the underlying concepts. Additionally, the effort has allowed the European tsunami community to coordinate a number of new research efforts and infrastrucutral developments, which are of benefit for the global science in PTHA/PTRA.

In this presentation we will outline the results of AGITHAR's major deliverables, a compilation of research gaps in PTHA/PTRA and uncertainty communication, findings in interdisciplinary tsunami research cooperation, and a collection of current practices in PTHA/PTRA. Ideas and opportunities of sustaining AGITHAR's output into the future will be given.

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JP05b - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Probabilistic tsunami risk assessment from historical impact files: Mediterranean and connected seas

DOI: 10.57757/IUGG23-4034 - LINK

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[3]*Natural Hazard Center- University of Pretoria, Natural Hazards Department, Pretoria, South Africa*

Probabilistic tsunami risk is assessed using a procedure that allows including mixed data from the instrumental part of tsunami catalogs, and data from the highly incomplete and uncertain pre-instrumental part. Such a model was used successfully for hazard assessment of earthquakes (Kijko et al., 2016) and tsunamis (Smit et al., 2019), considering seismic magnitude and tsunami height as metrics of the respective hazards. We applied this technique using catalogs for the basins of the Mediterranean and connected seas. Wave impact (destructiveness) is expressed in terms of tsunami intensity, K, i.e., a risk metric on the Papadopoulos-Imamura 12-degree scale. Risk level is assessed in terms of probabilities of exceedance and return periods of certain intensity levels in specific time frames. Tests and sensitivity analysis showed that using complete data sets generally provided more realistic results than using entire data sets. Our results indicated that the risk level depended on the seismicity level and not on the size of the investigated basin. The highest tsunami risk level was found in the eastern Mediterranean, with a significantly lower risk in the western Mediterranean. In the Marmara Sea, the tsunami risk was low, and the lowest was in the Black Sea. The risk in the Corinth Gulf in Central Greece was comparable to that of WM. The return period of damaging tsunamis was 22 years in the entire Mediterranean basin and from 31 to 1 660 years in the various sub-basins.

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JP05b - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Role of tsunami-tide interactions in evaluating tsunami hazard for Anchorage and Upper Cook Inlet, Alaska

DOI: 10.57757/IUGG23-2129 - [LINK]

Elena Suleimani[1], *Dmitry Nicolsky*[1], *Michael West*[1]
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The historic tsunami events have led to a common misconception that the Upper Cook Inlet (UCI) is completely immune to tsunami impacts. A coordinated effort is now underway to evaluate tsunami hazards in the area, as a part of the Alaska tsunami inundation mapping program.

Tsunamis were not reported in Anchorage during the Great Alaska earthquake. The 1964 rupture did not produce a substantial amount of slip in the presently creeping Kenai segment of the plate interface, which resulted in a relatively small amount of energy entering Cook Inlet. Another potential reason for the unreported tsunami was the timing of the arrival of the wave: after midnight at low tide.

Tsunami inundation models used in hazard assessment studies usually employ static-tide runs with the Mean High Water vertical datum, because dynamically coupled tsunami-tide models are hard to implement. However, UCI is a shallow water body with extreme tidal ranges of up to 10 meters, which makes tsunami-tide interactions crucial for accurate hazard assessment. We perform numerical modeling of the 1964 tsunami in UCI by dynamically coupling the tsunami model with tides, and suggest that a 3-meter high tsunami did occur, but was unnoticed in Anchorage due to its arrival on low tide that was 5 meters below Mean Sea Level. Our further modeling shows that the inundation zone, corresponding to the tsunami calculated on a high static tide, is larger than that computed with dynamically coupled tide, therefore our tsunami inundation maps do not underestimate potential hazard due to static-tide modeling.

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JP05b - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Deep learning of tsunami building damage from multimodal physical parameters for real-time damage assessment

DOI: 10.57757/IUGG23-2256 - LINK

Ruben Vescovo[1], *Erick Mas*[1], *Bruno Adriano*[1], *Shunichi Koshimura*[1]
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Tsunami building damage estimates are critical to post-disaster supply logistics and disaster management. Likewise, accurate damage estimates in a digital twin framework (Koshimura et al., 2023) enable more effective responses to disaster emergencies. However, meaningful results from an eventual disaster digital twin would be contingent on real-time inputs, at best. Hence, any practical implementation of a model that performs tsunami building damage estimates precludes reliance on post-disaster data, such as current damage detection models. By embedding physical representations of both the inundated environment and the tsunami, we propose to circumvent the limitations of optical imagery-based deep learning models. We aim to curtail the reliance on post-event data during evaluation, limit the constraints associated with the observation angle, and learn multi-level damage representations based on spatial and geophysical context. Our purpose is to learn these representations by training on physical parameters rather than optical imagery. Thus, we adapt deep learning architectures, initially developed for computer vision tasks, to take in a larger input tensor. Then, we extend and combine remotely sensed data, such as digital elevation models, land use, and cadastral maps. These extra layers embed the physical and spatial context relevant to tsunami inundation in the input. Finally, we test our modified architecture and benchmark the results against a random forest baseline.

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JP05b - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Building damage estimation using RaySAR, a Synthetic Aperture Radar simulator

DOI: 10.57757/IUGG23-2246 - LINK

Chia Yee Ho[1]*, Hannes Neuschmidt*[1]*, Erick Mas*[1]*, Bruno Adriano*[1]*, Shunichi Koshimura*[1]
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Typically, disaster response using remote sensing technology requires pre and post-disaster datasets. Unfortunately, pre-disaster data is not always available, and a lack thereof may lead to unreliable results in building damage predictions. Augmenting pre- and post-disaster data can artificially increase the training samples in machine learning (ML) models. In this regard, SAR simulators can provide synthetic data for augmentation purposes.

Here, we introduce a general framework for applying SAR simulators to building damage estimation. We used a SAR simulator, RaySAR, and optimized surface parameters, reflection, and a 3D model of the Onagawa Nuclear Power Plant, where the 2011 Tohoku tsunami hit, to assess the reliability of the SAR simulator compared to an actual SAR image. In addition, we constructed 3D models of damaged buildings with multiple damage statuses of the European Macroseismic Scale (EMS-98) to evaluate the suitability of the simulator for representing earthquake and tsunami damage. We strive to improve the original simulator using a more capable rendering algorithm, path tracing, and incorporation of Graphics Processing Units (GPUs) to achieve higher realism in diffuse reflections and shorter computation times. The results are evaluated using similarity measures in the spatial and frequency domains, contrasting simulated with authentic SAR imagery.

Preliminary results show that in simulated SAR imagery, damaged and undamaged buildings show distinguishable signatures. We believe that our simulator overcomes the limitations of the diffuse reflection model employed in RaySAR. Conclusively, the proposed framework seems promising for improving damage mapping in the context of future digital twin implementations.

Typically, disaster response using remote sensing technology requires pre and post-disaster datasets. Unfortunately, pre-disaster data is not always available, and a lack thereof may lead to unreliable results in building damage predictions. Augmenting pre- and post-disaster data can artificially increase the training samples in machine learning (ML) models. In this regard, SAR simulators can provide synthetic data for augmentation purposes.

Here, we introduce a general framework for applying SAR simulators to building damage estimation. We used a SAR simulator, RaySAR, and optimized surface parameters, reflection, and a 3D model of the Onagawa Nuclear Power Plant, where the 2011 Tohoku tsunami hit, to assess the reliability of the SAR simulator compared to an actual SAR image. In addition, we constructed 3D models of damaged buildings with multiple damage statuses of the European Macroseismic Scale (EMS-98) to evaluate the suitability of the simulator for representing earthquake and tsunami damage. We strive to improve the original simulator using a more capable rendering algorithm, path tracing, and incorporation of Graphics Processing Units (GPUs) to achieve higher realism in diffuse reflections and shorter computation times. The

results are evaluated using similarity measures in the spatial and frequency domains, contrasting simulated with authentic SAR imagery.

Preliminary results show that in simulated SAR imagery, damaged and undamaged buildings show distinguishable signatures. We believe that our simulator overcomes the limitations of the diffuse reflection model employed in RaySAR. Conclusively, the proposed framework seems promising for improving damage mapping in the context of future digital twin implementations.

JP05c - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Digital-Twin development for Probabilistic Tsunami Forecasting

DOI: 10.57757/IUGG23-3607 - LINK

Finn Løvholt[1], Manuela Volpe[2], Stefano Lorito[2], Jorge Macias[3], Manuel Castro[3], Andrey Babeyko[4], Steven Gibbons[5], Alice Gabriel[6], Jörn Behrens[7], Anne Mangeney[8], Francisco Hernandez[9]
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Probabilistic Tsunami Forecasting (PTF) combines early estimates of earthquake parameters with ensembles of urgent tsunami propagation simulations through the Tsunami-HySEA model. In the present implementation, the PTF is initialised by the earthquake information, but not updated further with new data. In the recently started Horizon Europe project DT-GEO work has started upgrading it into a Digital Twin providing a time dependent update of the model when new data becomes available. This enables a close to real time synthesis of data products and numerical models, continuously updating the model forecast as new data are continuously assimilated. In DT-GEO, an extended set of data sources, including improved earthquake solutions, sea level tsunami data, and GNSS, will be integrated. Secondly, the Digital Twin will implement a modularised inclusion of improved wave and source physics through dispersion, non-hydrostatic tsunami generation, inundation, improved earthquake physics, and cascading earthquake triggered landslide tsunamis. The model will be tested at site demonstrators, in the Mediterranean Sea for eastern Sicily and Samos, and in the Pacific Ocean for Chile and Japan. The presentation will explain how the PTF as it works today, followed by an outline of the design of the components in the Digital Twin. The presentation will finally describe initial improvements and plans for further development, including long term plans such as potential integration into Destination Earth and service provision within EPOS-ERIC. This work is supported by the European Union's Horizon Europe Research and Innovation Program under grant agreement No 101058129 (DT-GEO, https://dtgeo.eu/).

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JP05c - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Developing a deep learning super-resolution framework for tsunami inundation forecasting

DOI: 10.57757/IUGG23-2187 - LINK

Bruno Adriano[1], Shunichi Koshimura[1]
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Real-time forecast of tsunami inundation in a high-resolution domain, e.g., meter or sub-meter resolution, is essential for efficient evacuation procedures and damage assessments. Current approaches to real-time tsunami forecast are based on two conventional approaches; one is high-performance computing (HPC) to accelerate numerical tsunami calculations, and the other is building a large database of tsunami scenarios for specific areas of interest. However, these approaches have three significant drawbacks. First, HPCs are not primarily available in developing countries, especially for disaster management purposes. Second, the tsunami database must be constantly updated for accurate prediction because urban environments constantly change. Third, both approaches focus primarily on estimating coastal tsunami height or, at best, inundation depth at moderate resolution (e.g., greater than 10 m). We propose a novel deep learning-based system to address the above drawbacks by integrating advanced deep neural network algorithms and high-resolution numerical tsunami simulations. We developed an advanced deep neural network that analyzes pre-computed tsunami scenarios. The pre-computed scenarios include pairs of high-resolution inland inundations and corresponding coarse offshore tsunami heights and inundations. The network learns to estimate the high-resolution inundation based on corresponding patterns in a coarse tsunami dataset. The network can generate tsunami inundation for extensive areas at less than 10 m resolution, achieving 80% accuracy for scenarios outside the pre-computed dataset. Moreover, our network requires only a coarse offshore tsunami height as input, which allows easy application on lightweight personal computers.

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JP05c - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Multi-area applicability of machine learning-based immediate tsunami prediction

DOI: 10.57757/IUGG23-2299 - LINK

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Machine learning is one of the methods employed for the immediate prediction of tsunami occurrence. There have been few studies on error evaluation focusing on the arrival time of the tsunami inundation. In this study, we used machine learning to predict the tsunami arrival times for two areas and evaluated the errors. Tsunamis were calculated for several thousand cases for three different earthquake sizes using the tsunami simulator Q-Wave and assuming a Nankai Trough earthquake. Using these data, we trained a neural network to predict tsunami arrival time on the basis of the initial water level. As the amount of training data increased, the error decreased and the model with the most training data was used to predict the tsunami arrival times for two areas. The errors tended to be particularly large in coastal areas where tsunamis often reach. In some cases, the error was larger in Area B than in Area A, even though the amount of data for Area B was double that of Area A. These errors may be ascribed to variations in the arrival time of tsunamis in the training data due to topographical characteristics. For a magnitude 9.0 earthquake, the standard deviation of the tsunami arrival time in Area B is approximately 1.5 times that of Area A. Therefore, in addition to increasing the number of output variables and the accuracy of tsunami simulation, a more detailed consideration of the effect of area-specific characteristics on the error is needed in the future.

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JP05c - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Coastal Tsunami Prediction in Tohoku Region, Japan, Using S-net Observations based on Artificial Neural Network

DOI: 10.57757/IUGG23-2222 - LINK

Yuchen Wang[1], Kentaro Imai[1], Keisuke Ariyoshi[1], Takuya Miyashita[2], Narumi Takahashi[1]
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Seafloor observation network for earthquakes and tsunamis along the Japan Trench (S-net) was installed offshore Japan. It provides observations for tsunami early warning. Coastal tsunami prediction using offshore tsunami observations contains two main types: tsunami inversion (Tsushima *et al.*, 2009) and tsunami data assimilation (Maeda *et al.*, 2015). The first type must consider the source information, whereas the second type is affected by coseismic deformation. Recently, artificial neural network was introduced to tsunami prediction (Mulia *et al.*, 2020).

We adopted a denoising autoencoder (DAE) model for coastal tsunami prediction. It is a neural network with the encoder-decoder structure trained to denoise or correct corrupted data. We used 1,000 stochastic earthquake models (M7.0–8.8) in Tohoku region, Japan, and calculated synthetic tsunami waveforms at 50 S-net stations and two coastal stations. The DAE model was trained using 800 synthetic scenarios. Then, we tested the model against 200 unseen synthetic scenarios and two real tsunami events: the 2016 Fukushima earthquake and the 2022 Tonga volcanic eruption.

DAE model accurately predicted coastal tsunami waveforms for synthetic events. The maximum amplitude was accurately predicted for the 2016 Fukushima tsunami with a forecast accuracy of over 90%. The entire waveforms were also fairly predicted. However, coastal waveforms were not satisfactorily predicted for the 2022 Tonga volcanic tsunami, likely due to its different generating mechanism (i.e., meteorological tsunami). Our research is the first study to apply artificial neutral network to tsunami prediction using real observations. In the future, we will adopt more tsunami scenarios for model training.

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JP05c - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami forecasting method using time averages of dense ocean bottom pressure data (S-net)

DOI: 10.57757/IUGG23-0638 - LINK

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A dense cabled observation network, called the seafloor observation network for earthquakes and tsunami along the Japan Trench (S-net), was installed in 2017. Since then, the tsunami forecasting methods using S-net data have been developed vigorously. Especially, tsunami assimilation techniques or waveform inversion techniques to obtain tsunami initial conditions were newly developed. However, the ocean bottom pressure data are always contaminated by non-tsunami components such as sea-bottom acceleration change, ocean acoustic wave or P wave due to the earthquake. Therefore, tsunami components are needed to be separated from those non-tsunami components before those recent tsunami forecasting methods are applied.

In this study, we developed a new tsunami forecasting method using the time average of ocean bottom pressure data (S-net). Therefore, pre-data process to eliminate non-tsunami components form original data is not necessary. To test our method, tsunamis from the various fault models distributed along the plate interface along the Japan Trench were first computed. Then, time averages of computed ocean bottom pressure data at S-net stations were calculated by changing the time average windows. Second, tsunami initial conditions, initial ocean surface deformations, were estimated using interpolation of those time averaged ocean pressure data at S-net stations. Third, forecasted tsunamis were computed from those estimated tsunami initial conditions. Finally, forecasted tsunami waveforms along the coast were compared with the tsunami waveforms computed from the fault model at first. We conclude that this tsunami forecasting method performed well in general with some underestimations of tsunami heights along the coast.

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JP05c - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Modifying the pre-computed tsunami database for real-time tsunami forecasting after the 2016 off-Fukushima earthquake by an unpredicted mechanism

DOI: 10.57757/IUGG23-0781 - LINK

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On 22 November 2016, an intraplate normal-fault earthquake with a magnitude (M_{JMA}) of 7.4, with a tension axis in the northwest-southeast direction (hereafter, 2016 off-Fukushima earthquake), occurred east of the Fukushima Prefecture, Japan. However, the tsunami database (TDB), which contains pre-calculated tsunami data used for real-time tsunami forecasting by the Japan Meteorological Agency, had assumed that earthquakes in the Fukushima region were north-south oriented reverse fault type. The earthquake mechanism of the 2016 off-Fukushima earthquake differs from the predictions made in the TDB. Although the incorrect classification of normal and reverse faults did not affect the real-time tsunami prediction, the difference in fault plane strike was the main cause of the underestimated height prediction for Miyagi Prefecture. An efficient scenario arrangement is achieved when the differences in predictions from adjacent scenarios in the TDB are similar. Sensitivity analyses of tsunami height distribution to fault parameters for the 2016 off-Fukushima earthquake revealed the importance of the fault plane strike [1]. Therefore, adding earthquake tsunami scenarios with different fault plane strikes and the same epicentre near the epicentral area is reasonable. We compared the centroid moment tensor solutions for earthquakes with a moment magnitude of 5.5 or more that occurred in the coastal area around Japan between September 1994 and April 2017 with the fault parameters assumed in the TDB. Afterwards, we added scenarios to the TDB for regions where the difference in strike directions was observed to be 30° or more.

Reference:

[1] Hayashi, J. JSCE, B2-77(2),I_187-I_192, 2021. (in Japanese with English Abstract)

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JP05d - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Advances of the lattice Boltzmann methods (LBM) in tsunami modeling -present and future-

DOI: 10.57757/IUGG23-1502 - [LINK]()

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The lattice Boltzmann method (LBM) is an alternative computational fluid dynamics to conventional approaches to solve macroscopic equations. Despite various successful applications in many engineering fields, the LBM for tsunami modeling is still under development. In this study, we present the recent advances of the LBM for tsunami modeling and discuss future development. Tsunami involves various scales of fluid dynamics. Therefore, tsunami simulation methods have to be a unified method that covers the whole process from its generation to inundation. To achieve this goal, we present and discuss (i) the three-dimensional (3D) nonstatic pressure free-surface model, (ii) the two-dimensional (2D) shallow water model, and (iii) the hybrid 2D-3D model by the LBM for tsunami modeling. First, we develop the volume of fluid (VOF) based free-surface model using the cumulant model in the 3D LBM. We demonstrate that the cumulant LBM accurately calculates the impact pressure acting on a structure in violent flow fields. Second, we develop a shallow water model by 2D LBM and apply it to simulate the 2011 tsunami off the Pacific coast caused by the Tohoku earthquake. We demonstrate that the 2D LBM reproduce the tsunami propagation and inundation with an accuracy equally as good as that of the finite difference method. Finally, we develop a coupling 2D-3D LBM method and apply it to dam-break flow. We demonstrate that the proposed method connects 2D and 3D models. Then, we conclude that the LBM is valuable for the unified tsunami modeling method and provide the future direction.

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JP05d - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Impact of tsunami measurements from dense offshore network on modeling of tsunami source and propagation

DOI: 10.57757/IUGG23-1610 - LINK

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We investigated impact of dense seafloor observation network along the Japan trench, S-net, on tsunami generation and propagation modeling. We focused on the 2016 Mw 6.9 off-Fukushima earthquake, Japan, which generated the largest tsunami in this subduction zone after the S-net deployment. We inverted the offshore tsunami waveforms for the accurate tsunami source, and then used it in numerical tsunami simulation to clarify how well the tsunami waveforms recorded at the coastal sea-level stations can be reproduced. The results showed that the simulated tsunami waveforms matched the observations well for 90 min from the tsunami arrival time at each station, whereas the reproducibility in the temporal variation of tsunami energy over the long duration, including the decay process, varied from station to station. Because the discrepancies between the observations and calculations exceed the uncertainties due to the source estimation error, our results suggest the room for improvement in the propagation modeling. Another insight we found thanks to the offshore-data-constrained tsunami source is that the leading parts of the coastal tsunami waveforms might have non-negligible effect from the tsunami nonlinearity although they are often fed into linear tsunami inversion. This study has demonstrated that tsunami data from dense offshore network can contribute not only to accurate reproduction of targeted tsunami event, but also to the performance evaluation of the present source and propagation modeling technologies.

We used offshore and coastal tsunami data provided by NIED, MLIT, GSI and JMA. This work was partially supported by JSPS KAKENHI Grant Numbers JP19H02409 and JP21K04621.

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JP05d - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Reconstruction of initial tsunami source from the runup evolution at the coast

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The study of long wave runup is a classical problem in fluid dynamics, in both its linear and nonlinear formulations. On the other hand, little attention has been given to the inverse problem, i.e. the reconstruction of the initial condition from a known runup time history.

According to the piston model of tsunami generation, the problem can be modelled as an initial value problem with assigned initial water surface displacement and zero velocity. In this framework, the solution of the linear problem, i.e. the runup as a function of time, can be written as the convolution of the initial water surface with an Abel kernel. This solution can be analytically and uniquely inverted, obtaining the initial wave surface as a functional of the runup function.

In this work, this solution is applied to analytically generated runup time series and its properties are analyzed. In particular, the robustness of the solution to added noise is verified and the effect of nonlinearity is investigated through the use of a Riemann transform of the coordinates.

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JP05d - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Uncertainties in a paleoearthquake modeling

DOI: 10.57757/IUGG23-2557 - LINK

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For modeling a paleo earthquake-tsunami event, tsunami inundation areas by assumed sources for the paleo earthquake can be estimated along coastal areas where tsunami deposits were identified for the event. An earthquake source scenario among them with the best inundation area for the distribution of tsunami deposits can be determined as a reasonable source scenario of the earthquake. The estimated inundation area, therefore, has an important role in the development of source scenario and, however, strongly reflects numerical effects such as a grid size and types of governing equations. This study targets a tsunami generated by the great earthquake in the 17th-century in Hokkaido, Japan, and discusses how such effects impact the development of the earthquake source scenario.
At a coastal site of eastern Hokkaido, where tsunami deposits for the event were found, we compared tsunami inundation areas simulated under several source scenarios by shallow water and Boussinesq models in different-sized grid systems. Results indicated that tsunami propagation and inundation patterns even from an identical source might be variable greatly owing to the model differences. Existing studies estimated an inundation area expected in the 17th-century tsunami at the site, as well as other sites, and proposed source scenarios of the earthquake by accounting for the results. However, the results of this study suggested that non-identical tsunami propagation and inundation patterns from the identical sources proposed by them could be produced owing to the model differences. Therefore, the source scenarios may include large uncertainties associated with the numerical effects.

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JP05d - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Boulders motion under breaking solitary waves

DOI: 10.57757/IUGG23-2007 - LINK

Pin-Tzu Su[1], *Ira Didenkulova*[1], *Atle Jensen*[1]
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Impact of solitary breaking waves on partly submerged boulders is studied experimentally in a small wave tank. Focus is on the forces and motion of boulder with different size. Furthermore, sand is added which change the friction coefficient. Experiments are conducted at the Hydrodynamics lab at the University of Oslo in a small 3m long and 10 cm wide wave tank, filled with 5 cm water.A block releasing mechanism generates solitary waves with an amplitude normalized by the water depth a/h = 0.47. The dimensions of the block are 15.03 cm, 10 cm and 5.00 cm (length, width, height). Generated solitary waves propagate to a 1:10 beach. Boulders of different size, volume and orientation are placed alternately (one at a time) at different locations on the beach slope (smooth or sandy) with respect to the wave breaking point. The transport of boulders and their motion is studied with respect to the boulder characteristics (volume, size, orientation), inclusion of sand and the initial position of the boulders. The sand on the slope changes bottom friction, and therefore, increases the boulder transport. Overall, the effects of boulders' length (parallel to wave direction) on the displacement of boulders are more evident in this study.

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JP05d - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Understanding tsunami resonance at bay scales through stochastic simulations

DOI: 10.57757/IUGG23-4074 - LINK

Patricio Catalan[1], Mauricio Diaz[1], Natalia Zamora[2], Rodrigo Cienfuegos[3], Matias Carvajal[4]
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[2]Centro Nacional de Supercomputacién, Barcelona Supercomputing Center, Barcelona, Spain
[3]Pontificia Universidad Católica de Chile - CIGIDEN,
Departamento de Ingeniería Hidráulica y Ambiental, Santiago, Chile
[4]Pontificia Universidad Catolica de Valparaiso, Instituto de Geografia, Valparaiso, Chile

The role of resonance has been long recognized as a relevant aspect in controlling the duration and other inundation metrics of tsunami response. However, whether their site-specific behavior is controlled by the source or the morphology is challenging to be determined owing to several reasons. First, in situ data to carry out the characterization can be only obtained during tsunami events, and it is usually spatially sparse, thereby limiting generalization. Moreover, distinguishing between source and bathymetric control is possible in these cases even though both signals are intermingled, but whether the resulting amplification will be similar for other events is debatable. Alternatively, analytical or numerical methods can identify multiple modes dominated by the bathymetry. However, distinguishing which ones would dominate the actual response remains a challenge because earthquake source characteristics are usually absent.

In this work, we take advantage of using a large number of stochastic earthquake simulations to drive a NLSWE numerical model to identify response trends on a set of different bays in Central Chile. We couple these results with a free oscillation model and historical data to validate some cases. Results show that bays can be classified as being bathymetry-controlled, source-controlled, or a mixture of both, depending on how consistent their response is when magnitudes and rupture distributions are varied. Such characterization could help in understanding site-specific hazards, as a first step to mitigation.

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JP05e - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Source modeling of the 2018 Anak Krakatau tsunami based on an inversion analysis

DOI: 10.57757/IUGG23-0628 - LINK

Tatok Yatimantoro[1], Yusuke Yamanaka[1], Yuichiro Tanioka[1], Dwikorita Karnawati[2]
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[2]Indonesian Agency for Meteorology- Climatology- and Geophysics, Department of Geophysics, Jakarta, Indonesia

Real-time tsunami estimation in volcanic events remains challenging because modeling the tsunami generation process in real-time is greatly uncertain. In this study, we investigated the performance of a tsunami waveform inversion method that can estimate an initial sea surface deformation useful for real-time estimation in a volcanic-induced tsunami event. As a case study, we focused on the 2018 Anak Krakatau event, which had a tsunami resulting in a large number of casualties in Indonesia.

We assumed a source area located around the collapsed area of Anak Krakatau and assigned point sources with the Gaussian shape as a basis function. Propagation of the point sources was individually solved based on the linear longwave equation to estimate Green's functions at four tide gauge stations where the 2018 tsunami was observed. Based on an inversion analysis using the observed waveforms and Green's functions, we obtained an initial sea surface deformation producing reasonable tsunami waveforms at the tide gauge stations. Our estimated deformation peaked at the southwestern part of the Anak Krakatau volcano, consistent with tsunami generation areas reported by prior studies for this event. Additionally, our inversion analysis successfully reproduced the observed waveforms better than those from an existing study, which conducted a similar analysis to ours.

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JP05e - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Development of real-time forecasting method for anak krakatau volcanic-induced tsunamis, Indonesia

DOI: 10.57757/IUGG23-0646 - LINK

Rinda Nita Ratnasari[1], *Yuichiro Tanioka*[1], *Yusuke Yamanaka*[1]
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Early warning systems should be available for volcanic tsunamis. Present tsunami warning systems have been specialized for earthquake-generated tsunamis, and it remains challenging to rapidly evaluate the tsunami potential accompanied by a volcanic eruption and/or volcanic sector collapse. By targeting the volcanic sector collapse of Anak Krakatau in 2018, which generated a large tsunami as a case event, we develop a real-time forecasting method for tsunamis accompanied by such eruptions in Indonesia. The proposed forecasting method is based on the utilization of observation stations near the source area and a pre-computed database. In this study, six virtual observation stations were placed in the vicinity of the volcano. Then, a pre-computed waveforms database was constructed from various collapse scenarios using a numerical simulation of sector collapse and tsunami propagation. In the real application, tsunami forecasting computation will be conducted using the initial conditions which are selected from the best combination of scenarios inside the database through waveforms fitting at six observation stations. The reliability of the method was examined using three hypothetical collapse scenarios of Anak Krakatau assuming three different sliding directions. Based on numerical experiments, the forecasted tsunami along the coast of Java and Sumatra by our method resulted in satisfactory performance. Our results indicate that the combination of a pre-computed database and the existence of observation stations near the source area was able to produce appropriate tsunami forecasting for the coastal area. We conclude that our method has a reasonable predictive skill for volcanic-induced tsunamis in Anak Krakatau.

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JP05e - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Landslide induced tsunami hazard at volcanoes – the case of Santorini

DOI: 10.57757/IUGG23-3636 - LINK

Ocal Necmioglu[1], Mohammad Heidarzadeh[2], Georgios E. Vougioukalakis[3], Jacopo Selva[4]
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[4]University of Naples Federico II, Department of Earth- Environmental- and Resources Sciences, Naples, Italy

The destructive tsunami on 22 December 2018 due to the flank collapse of the Anak Krakatau volcano was a bitter reminder of large tsunami risks and of the shortcomings of the existing tsunami warning systems for atypical (non-seismic) sources. In the Mediterranean, several tsunamis were generated by landslides associated with volcanic systems in the past.The volcanic unrest experienced in 2011-2012 on the Santorini volcanic island in the Southern Aegean Sea pointed out the need to identify and quantify tsunami hazard and risk due to possible flank instability which may be triggered as a result of volcanic unrest or nearby seismotectonic activities. Inspired from this need, in this study we examined three possible landslide scenarios in Santorini Island with tsunamigenic potential. The results show that the scenarios considered in our study are able to generate significant local tsunamis impacting Santorini and the nearby islands, as well as producing significant impact along the coasts of the Southern Aegean Sea. While maximum tsunami amplitudes/arrival time ranges are 1.2m/30-90min for locations in the Greek-Turkish coasts in the far field, they are in the order of ≈60m/1-2min for some locations at the Santorini Island. The extreme tsunami amplitudes and short arrival times for locations inside the Santorini Island is a major challenge in terms of tsunami hazard warning and mitigation. As an effort to address this challenge, a discussion on the requirements for local tsunami warning system addressing atypical sources in the context of multi-hazard disaster risk reduction is also provided.

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JP05e - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Numerical simulation of landslide tsunamis using smoothed particle hydrodynamics

DOI: 10.57757/IUGG23-0459 - LINK

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Tsunamis can be generated by mass movement such as slide, slump, and sector collapse. The recent events of such “landslide tsunami” include Papua New Guinea tsunami in 1998, Sulawesi tsunami and Krakatau tsunami in 2018. In order to estimate how landslide tsunamis affect buildings and infrastructures, it is required to predict and analyse both landslide and tsunami accurately. This work presents the numerical simulation of landslide tsunamis using Smoothed Particle Hydrodynamics (SPH).

SPH is a particle method which is suitable for simulating multi-physics and large deformation problems. DualSPHysics, one of the opensource code of SPH, was used in the numerical simulation. DualSPHysics has the non-Newtonian fluid model and the Discrete Element Method (DEM) coupling, which can be accelerated by GPU. In this work, the non-Newtonian fluid model was applied to underwater landslide cases, and the SPH-DEM coupling was utilised to analyse subaerial landslide tsunamis. The results were compared with the existing experiment data. Landslide motion and tsunamis were successfully simulated in both underwater and subaerial landslide cases. Overall, the time series of water level agreed with the experimental results. Further investigation and future developments will be discussed.

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JP05e - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Estimating the scale of submarine landslide tsunamis in the Sea of Japan

DOI: 10.57757/IUGG23-0783 - LINK

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The Sea of Japan contains traces of submarine landslide collapses of various sizes, some of which may have caused tsunamis in the past. Many important infrastructure facilities are located in coastal areas of Japan. Therefore, it is very important for disaster prevention to estimate the risk of tsunamis caused by submarine landslides that may occur in the future. The objective of this study is to establish a method for estimating the scale of tsunamis generated along the Sea of Japan coast using trace data from past submarine landslides.

We examined data from about 1,500 submarine landslide sites in the Sea of Japan and were able to extract about 300 sites whose longitudinal profiles clearly had the shape of landslides. Then, using parameters such as water depth, slope angle, landslide width, and volume, the initial tsunami characteristic amplitude, which is the maximum depression of the free surface above the submarine landslide, can be calculated. In this study, the equation of Watts et al. (2005) was used to estimate the scale of tsunamis caused by submarine landslides.

As a result, the tendency of tsunamis caused by submarine landslides varies from region to region. Large-scale tsunamis were found to be concentrated in southwestern Hokkaido, while medium-scale tsunamis were found to be distributed over a wide area. In the presentation, we will also show an example of estimating the return period and magnitude of submarine landslide tsunamis in the Sea of Japan by probabilistic evaluation using the Monte Carlo approach.

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JP05f - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

On self-induced transparency in weakly nonlinear meteotsunami shoaling

DOI: 10.57757/IUGG23-1220 - LINK

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Meteotsunamis are long waves generated by atmospheric perturbations (scales of O(1 -10 km) and O(1 min to 10 min); e.g.Rabinovich and Monserrat 1996, 1998; Sheremet et al. 2016). Their amplitudes over the shelf are small O(1 cm) but may increase by shoaling to O(1 m) at shoreline. Often meteotsunamis evolve into `dispersive shock' (`solibore'). The constituent solitary waves are much smaller scale than the original wave. For the most of the meteotsunami evolution over shelf there is practically no reflection, the dynamics is well described by the KdV with variable coefficients. The reflection occurs in the areas with relatively steep bottom gradients. The magnitude of metotsunami hazard depends on reflection/transmission at such areas. Here we study meteotsunami reflection at the shoreline. The commonly observed generation of solibores implies that a sizeable part of meteotsunami energy is transferred to smaller scale waves, for which reflection is significantly reduced, and conversely, the energy transmitted to the shoreline (meteotsunami hazard) significantly increased. The phenomenon is similar to the self-induced transparency (Kocharovskaya and Khanin, 1986; a process that allows propagation in a normally opaque medium) but with entirely different physics: the large scale, small amplitude wave is reflected, while small scale, finite amplitude waves reach the shore. We investigate the sensitivity of the process to propagation parameters and quantify the reflected/transmitted energy.

Rabinovich AB, Monserrat S (1996) Nat Hazards 13(1):55–90
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JP05f - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

3.11 Densho Road Promotion Organization to transfer experiences and lessons

DOI: 10.57757/IUGG23-0374 - LINK

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In the areas affected by the 2011 Tohoku Earthquake and tsunami, there are remains of earthquake disasters and traditional facilities scattered over a vast area spanning multiple prefectures in Tohoku, and it is not easy to visit them in a limited amount of time. Therefore, it is necessary to classify and provide information on traditional facilities, install guide maps and signs, and create a network so that visitors can visit and inspect facilities efficiently according to their purpose and time. The 3.11 Densho Road Promotion Organization, a general foundation, was started. In order to learn the lessons of the 2011, we aim to carry out various activities and projects related to disaster prevention by utilizing the network of disaster lore facilities. There are many remains and exhibition facilities for learning the actual situation and lessons of the disaster. Based on its facilities and networks, this promotion organization plays a central role in carrying out various initiatives and projects related to "learning" and "preparation" for disaster prevention, mitigation, and tsunamis. It is very important to convey the damage situation and experience of the great earthquake, the emergency response at the time, and the ongoing recovery and reconstruction activities both domestically and internationally and leave them to future generations.

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JP05f - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Effective visitor learning from disaster tourism in the 2011 Tohoku Earthquake and Tsunami

DOI: 10.57757/IUGG23-1276 - LINK

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The importance of passing on lessons from the disaster has been emphasized in the areas affected by the 2011 Tohoku earthquake and tsunami. Since then, efforts have been made to promote the dissemination of disaster learning. However, it is unclear what kind of disaster education/learning is effective in changing behavior for disaster risk reduction and whether the content of effective disaster tourism differs depending on the content disseminated, visitors' interest, awareness of the disaster, preparedness, and the purpose of their visit. In this study, we aim to analyze the effectiveness of disaster learning and which contents of learning and experiences effectively change their actions to reduce disaster risk. We conducted an online survey among visitors (N=1,175) to the disaster-affected areas from the 2011 event to understand the contents of their learning and how their learning experience has influenced their actions to reduce their disaster risk. The main findings are as follows: 1) visiting the interior of the earthquake ruins, seeing the townscape that was cleared before the earthquake, and listening to the stories of locals who experienced the disaster was found to be most effective in promoting learning, regardless of the visitor's disaster preparedness or purpose; 2) informal and interactive interactions with locals who experienced the disaster may be effective for visitors whose purpose is not to learn about the disaster. Finally, two measures are proposed to enhance the effective communication of disaster memories and disaster risk reduction in the future.

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JP05f - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Extracting cascading consequences of the 2011 Great East Japan earthquake and tsunami using social sensing data

DOI: 10.57757/IUGG23-2242 - LINK

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Tsunami is a typical secondary disaster that can cause unpredictable consequences. After a large earthquake strikes, multiple disaster chains occur when one event triggers another, resulting in a wider and more severe impact than the initial strike. Although some studies have been conducted to analyze cascading effects, many potential impacts of cascading disasters remain uninvestigated from a social sensing perspective. In this study, we propose a method for identifying cascading disasters using natural language processing to extract causal relations comprehensively and objectively between events based on tweets and other auxiliary data, such as remote sensing and newspaper data. The applicability of this method is illustrated by employing data extracted from the Twitter official API on the 2011 Great East Japan earthquake and tsunami. Our methodology can be undertaken in four steps: (i) use relevant keywords to acquire data from Twitter API for the analysis period. (ii) clean and visualize the data, then, extract disaster causal knowledge via pattern matching. (iii) compare semantic and syntactic features and classify the casual and noncausal types using machine learning. (iv) create a disaster keywords database and get tsunami cascading event automatically by calculating cosine similarity between each sentence pair.Our method can effectively and automatically extract the broadest possible range of events during the early stages of the disaster by developing a tsunami event's relationship. Furthermore, the feature combinations that are most suitable for tweets can also be compared in this paper.

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JP05f - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami evacuation of connected and autonomous vehicles using flocking control algorithm

DOI: 10.57757/IUGG23-2252 - LINK

Daiki Hachiya[1], Kazuki Wako[2], Erick Mas[3], Shunichi Koshimura[3]
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The evacuation during the 2011 Great East Japan Earthquake and Tsunami revealed a high preference for vehicle evacuation in coastal areas. Although evacuation by foot is generally suggested, considering the contribution to evacuating vulnerable people (e.g., the elderly, infants, and disabled), it is essential to plan for safe and reliable evacuation by car. Connected and Autonomous Vehicles (CAVs) have a great potential to improve transportation system efficiency through autonomous driving and communication technologies. Assuming that CAVs will be widely used in the future, it is crucial to examine the impact of autonomous car evacuation on traffic flow (e.g., moving speed, evacuation time, and traffic capacity). In this study, we evaluate the effectiveness of CAVs in tsunami evacuation using the flocking algorithm as the primary control model. We developed a microsimulation of CAVs self-driving along a road with obstacles using agent-based modeling. Then, we quantitatively compared the CAVs model to a human driving control model as a baseline to assess its effectiveness. The results indicated that CAV flocking control performs better than the baseline in a three-lane roadway environment with obstacles. Applying the proposed flocking algorithm method and optimizing navigation-control parameters to various traffic situations, this study contributes towards investigating safe autonomous car evacuation in the future.

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JP05f - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Application of a global-based deep learning damage estimation using remote sensing data to unseen tsunami events

DOI: 10.57757/IUGG23-2184 - LINK

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Artificial intelligence, specifically deep learning (DL), has been increasingly used in remote sensing technology for rapid disaster assessment. Despite having high accuracy, the approach requires numerous samples to maintain its performance. However, in an emergency response phase, training samples are often unavailable. Moreover, generating ground truth data is laborious and time-consuming, which impedes the fulfillment of damage information for emergency response needs. Given this background, we utilized historical disaster events collected worldwide to recognize damage in new unseen locations. We compared the performance of multiple DL convolutional neural networks (e.g, ResNet34, ResNex, and SwinTransformer). We used the trained model to estimate the damage in the 2011 Tohoku Tsunami to illustrate the usefulness of both historical data and DL models for mapping a new disaster event. Preliminary results show that SwinTransformer outweighs the performance of others CNN-based models. The accuracy of the transformer-based model reaches 85% compared to 82% for both ResNet34 and ResNext. However, when the best performance model is tested on the 2011 Tohoku Tsunami, the performance drops to 23% accuracy. This reduction in accuracy may be attributed to the difference in sensing conditions and data distribution between the global and the Tohoku datasets.

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JP05g - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami seismology: Historical review and future direction

DOI: 10.57757/IUGG23-0171 - LINK

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Most tsunamis are generated by submarine earthquakes, and tsunami data are used to study earthquake sources. Tsunami waveform inversion was first proposed in the 1980s and has been applied to many earthquakes in the world. Tsunami speed is slower than typical rupture velocity of earthquake source, while seismic wave velocity is faster. This difference makes the tsunami waveform inversion more robust for spatial distribution, while the seismic inversion is more robust for temporal resolution. Global deployment of deep ocean bottom pressure gauges provides valuable data for tsunami waveform inversion, because they are free from coastal nonlinear effects. The effects of elastic earth on trans-oceanic tsunami propagation can now be accounted for.

Tsunami data are also useful for historical and prehistorical earthquakes. Coastal tsunami heights or inundation limits can be estimated from damage descriptions in historical documents, often without information on temporal evolution of tsunami. For paleo-tsunamis, tsunami heights and inland extent can be estimated from the distribution of tsunami deposits. Thickness and grain size distribution of tsunami deposits are also sensitive to the tsunami source parameters, hence can be used to study earthquake sources, through sediment transport modeling. While nonlinear effects must be considered, these methods are also valuable tools to study earthquakes in the past.

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JP05g - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Results of the international collaborative project on "Building earthquake and tsunami resilience in East Indonesia" and future directions

DOI: 10.57757/IUGG23-0022 - LINK

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[6]GNS Science, Earthquake and Tsunami, Lower Hutt, New Zealand

Eastern Indonesia suffers from significant tsunami hazards due to its complex tectonic setting characterized by several subduction zones, numerous active volcanoes, as well as submarine landslides. Following the two destructive tsunamis in Indonesia in 2018 in Palu and Sunda Strait, it has been urgent to address large tsunami hazards in this unique tsunamigenic zone. This presentation outlines the outcomes of an international collaborative project on "Building Earthquake and Tsunami Resilience in East Indonesia", supported by the Royal Society (UK) for the period 2019-2023. The project brought together research teams from UK and Indonesia, working together towards safer communities from tsunamis and earthquakes. The project mapped and studied seismogenic and tsunamigenic zones in East Indonesia, modelled scenarios of potential future tsunamis, and developed community resilience to tsunamis. A marine seismic survey was conducted in August 2022 to obtain seismic and bathymetric data from the region. The project also studied several recent earthquakes and tsunamis in the region, including the 14th November 2019 Molucca Sea tsunami following an Mw 7.2 earthquake, the 16th of June 2021 tsunami following an Mw 5.9 earthquake, and the 2018 Palu earthquake and tsunamis. It is believed that this project has generated a large database for earthquake and tsunami resilience studies in East Indonesia, and will inspire future research works. This research is funded by The Royal Society (the United Kingdom), grant number CHL/R1/180173 and Lloyd's Tercentenary Research Foundation, the Lighthill Risk Network, and the Lloyd's Register Foundation.

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JP05g - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Unique long-period tsunamis generated by the July 2020 and July 2021 Alaska-Aleutian megathrust earthquakes

DOI: 10.57757/IUGG23-0526 - LINK

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Two large earthquakes occurred in the Alaska-Aleutian subduction zone in July 2020 (*M*w 7.8) and July 2021 (*M*w 8.2), generating tsunamis characterized by considerably longer periods than that typically expected from their moment magnitudes. The 2020 earthquake resulted in approximately 40–90 min tsunami periods (Mulia et al., 2022, GRL; Heidarzadeh and Mulia, 2021, Ocean Eng.). Similarly, the 2021 event exhibited long-period tsunamis of >50 min (Mulia et al., 2022, SRL). For comparison, the April 2014 Illapel, Chile, earthquake (*M*w 8.2) and the November 2016 Kaikoura, New Zealand, earthquake (*M*w 7.8) produced tsunamis with dominant periods ranging from 15 to 21 min (Heidarzadeh et al., 2019, Ocean Eng.).

To reveal the underlying cause for such anomalous occurrences, we conducted an inversion analysis using tsunami and geodetic data. Our inversion results indicated the up-dip extent of both earthquakes confined at a depth of ~20 km of the plate interface, which corresponds to the shelf break on the surface. Therefore, the coseismic surface displacement predominantly took place at shallow water depths of ~200 m within the broad continental shelf extending ~120 km offshore. Consequently, it is responsible for the long-period tsunami waves as the water depth is inversely proportional to the period. This geophysical setting is uniquely attributed to the Alaska-Aleutian subduction zone, which is rarely found in other major subduction systems. References: https://doi.org/10.1029/2021GL094937; https://doi.org/10.1785/0220210359; https://doi.org/10.1016/j.oceaneng.2021.109243.

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JP05g - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami modeling of a potential seismic source on the north shore of Cuba

DOI: 10.57757/IUGG23-3615 - [LINK]

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On January 9, 2014 a M=5.1 earthquake occurred on the north shore of Cuba. The event was dip-slip on a WNW-ESE fault. The location is the site of offshore islands, oriented WNW-ESE, with a total length of 200 km. This suggests that larger seismic events are possible. The earthquakes are 90 miles (144 km) from the south shore of Florida. We modeled potential tsunamis from a fault oriented WNW-ESE and dipping 90 degrees. To represent shaking from a M=7.5 earthquake we used a length of 100 km, width 10 km, and slip 1.85 m. The modeling was performed using a numerical program (Nicolsky et al., 2011) at UAFGI. Results show heights of 3-8 cm at Key West, Everglades (ENP), Marco Island and Miami. Maximum heights of 0.4 m are observed near source. Travel times for initial wave are: ENP 15 min; Key West 28 min; Miami 30 min; Marco Island 240 min. The peak occurs 10-50 min later. We also modeled slip with reversed polarity (some aftershocks showed reverse slip); the models gave the same heights and times but reversed polarity. This is because the grid for bathymetry is coarse (3x3.7 km pixel size) so detailed interaction with the shore is not well represented. We modeled a larger event by increasing the slip. This resulted in a M=7.8 hypothetical event, with higher amplitudes but similar time histories. These results suggest that South Florida would experience only a modest hazard from tsunamis generated by earthquakes on the north shore of Cuba.

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JP05g - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Size and recurrence characteristics of the 1611 tsunami along the Pacific coast of southern Hokkaido indicated by tsunami deposit surveys

DOI: 10.57757/IUGG23-4888 - LINK

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Sandy tsunami deposits from the 1611 Keicho Oshu earthquake are distributed in peat at a depth of 50cm-1m in Atsuma, eastern Iburi, Hokkaido. The elevation at the time of the event was 3-4.5m, and it slopes gently inland. The thickness of the sediments is more than 50 cm at the thickest point, and it became thinner inland and invisible at about 500 m from the coastline ca. 200 years ago. Also, the mean grain size of the tsunami deposits becomes as fine as 3.5φ near the distribution limit. The size of the tsunami suggested by the properties of these deposits is about 5m in height, which is smaller than that in the tsunami scenario by the Cabinet Office (about 9m at the coast). Neighboring Tomakomai and Mukawa also show that the inland extent of the tsunami indicated by geological traces is significantly shorter than that drawn in the hazardmap. In these areas, no other possible tsunami traces could be discerned even on X-ray CT images during the past 2500 years, though known tephras (Ta-b; 1667 CE, Us-b; 1663 CE, B-Tm; 10th Century CE, Ta-c3; ca. 2000yr BP, Ta-c2; ca. 2500yr BP) were well-preserved. The new information about the 1611 tsunami in Atsuma, together with the research results in Tomakomai and Mukawa, provides important constraints for the size and recurrence interval of tsunamis in the northern part of the Japan Trench and is useful for the evaluation of source models of earthquakes and the damage estimation.

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JP05h - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

The global ocean-atmosphere tsunami event generated by the Hunga-Tonga eruption of 15 January 2022: An Overview

DOI: 10.57757/IUGG23-3173 - LINK

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A major submarine volcanic eruption occurred on 15 January 2022 in the vicinity of the Tonga-Kermadec Islands in the Tropical Pacific Ocean. The eruption produced tsunami waves that were recorded throughout the World Ocean, including the Caribbean, Mediterranean and Black seas. The event attracted considerable scientific attention. Several thousand sea level and atmospheric pressure records have been examined, as well as numerous other geophysical data. A unique feature of the tsunami waves measured by coastal tide gauges and open-ocean bottom pressure recorders was the dual forcing mechanism that sent both oceanic waves –induced directly by the eruption and radiating outward from the source at the longwave speed of ~200 m/s – and atmospheric Lamb waves that circled the globe several times at the speed of sound of ~315 m/s. This dual source resulted in marked tsunami waves with heights of 2.0-2.5 m on the Pacific coasts of Chile, the US , New Zealand, Japan and the Aleutian Islands. The "atmospheric" waves arrived first, but the direct oceanic waves were much higher. In the Atlantic and Mediterranean, the waves were mostly of atmospheric origin (except on the coast of Argentina). Numerical models of the event show generally good agreement with observation. Global maps also reveal regional "hot spots", where the tsunami heights were greatest. On the Atlantic Coast of the US, arrival of the Tonga tsunami coincided with hurricane generated waves to produce a hazardous double jeopeordy wave event.

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JP05h - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Modeling tsunami generation by moving pressure systems: Case studies and implications

DOI: 10.57757/IUGG23-4803 - LINK

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On January 15, 2022, the Hunga-Tonga Hunga-Ha'apai volcano generated unexpectedly strong tsunami that was recorded all over the Pacific Ocean and in other ocean basins, including the Caribbean and Mediterranean seas. Mounting evidence quickly pointed toward an unorthodox tsunami generation mechanism – forcing by propagating pressure anomalies from acoustic gravity waves (a.k.a atmospheric Lamb waves) originated from the volcanic blast.

The Lamb wave forcing of tsunami is similar to the formation of meteotsunamis from weather systems and to the gravity waves formation from other large atmospheric explosions like meteorite impacts, including the role of Proudman resonance to amplify the wave in certain directions. Those generation mechanisms have been studied before; however, the January 15, 2022 Tonga tsunami is the first event that proved the existence of air-pressure coupling mechanism for tsunami generation during the blast events. It also provided ample data for the model verification and testing for pressure-generated tsunamis. As the result, the ongoing modeling efforts to simulate the 2022 Tonga tsunami plays an important role in quantifying the hazard and possible mitigation measures for tsunamis generated by moving pressure disturbance.

Tsunami models simulating moving pressure generation mechanisms for volcanos, meteotsunamis, asteroid impacts are presented. Commonalities, differences and effectiveness of these sources for tsunami generation are considered. Potential hazard mitigation measures are discussed.

On January 15, 2022, the Hunga-Tonga Hunga-Ha'apai volcano generated unexpectedly strong tsunami that was recorded all over the Pacific Ocean and in other ocean basins, including the Caribbean and Mediterranean seas. Mounting evidence quickly pointed toward an unorthodox tsunami generation mechanism – forcing by propagating pressure anomalies from acoustic gravity waves (a.k.a atmospheric Lamb waves) originated from the volcanic blast.

The Lamb wave forcing of tsunami is similar to the formation of meteotsunamis from weather systems and to the gravity waves formation from other large atmospheric explosions like meteorite impacts, including the role of Proudman resonance to amplify the wave in certain directions. Those generation mechanisms have been studied before; however, the January 15, 2022 Tonga tsunami is the first event that proved the existence of air-pressure coupling mechanism for tsunami generation during the blast events. It also provided ample data for the model verification and testing for pressure-generated tsunamis. As the result, the ongoing modeling efforts to simulate the 2022 Tonga tsunami plays an important role in quantifying the

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JP05h - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Genesis of the 2022 Tonga volcanic tsunami

DOI: 10.57757/IUGG23-1328 - LINK

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The 2022 Tonga volcanic eruption generated a surprisingly large air-pressure wave (lamb wave) and a locally damaging tsunami. The tsunami generation is still puzzling because both the air wave and submarine explosion drove changes in sea level. Here we have derived observational evidence from satellite altimetry (a rarity for a volcanic tsunami), assisted by a combined atmospheric and oceanic tsunami model, to shed light on its genesis. We found that three satellites had captured the sea level signal of the tsunami: the AltiKa satellite observed the near-field tsunami, 29 minutes after the eruption, while the Sentinel-6 Michael Freilich and Jason-3 satellites in tandem 30 seconds apart captured the tsunami through the volcano center and encountered the tsunami wave at about 54°S about 5 hours after the eruption. We proposed a mass-conserving tsunamigenic mechanism, which couples the volcanic ejecta to ocean waters filling in the erupted crater, to reconcile the satellite observations with other in-situ measurements. We concluded that the erupted air-waves had increased the tsunami's destructive power through the inverted barometer effect during their overlapping period in the near field, and orchestrated the far-field disturbance in the Pacific Ocean and beyond. Our study also demonstrated an altimetry procedure to isolate tsunamis from ocean dynamic features and a data-based approach to quantify volcanic tsunami source for early warnings.

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JP05h - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Meteorological and volcanic tsunami signals generated by the Hunga Tonga-hunga Ha'apai eruption

DOI: 10.57757/IUGG23-0830 - LINK

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An eruption of the Hunga Tonga-hunga Ha'apai Volcanic Eruption on 15 January 2012 caused tsunami waves, observed globally in tide gage records. In this study we investigate the origin of tsunami waves through the analysis of tide gauge records and numerical simulations in the Indo-Pacific region. The atmospheric pressure wave (Lamb wave) due the eruption was recorded in meteorological stations across Australia. The moving pressure jump was recorded as a ~6.5-hPa jump at the Norfolk Island; ~3.5 hPa at Broken Hill, NSW and Perth and was estimated to be travelling at ~340 ms^{-1}. In the deep ocean this allows for Proudman resonance between the ocean and atmosphere generating a meteotsunami propagating westward across the Indian Ocean. Tide gauges located across the whole Indian Ocean basin recorded the meteotsunami generated by the pressure jump. There were two distinct signal on the tide gauge records. The first signal was recorded in advance of the predicted volcanic tsunami along the east coast of Australia and was due to the meteotsunami. The arrival of the second signal corresponded to tsunami wave generated by the displacement of the volcano travelling as a 'free' wave. These findings were confirmed by numerical simulations using an ocean circulation model that incorporated a moving atmospheric pressure jump travelling at a speed of ~ 340 ms^{-1}. The long ocean waves were amplified due to Proudman resonance in the deep ocean, where the water was deeper than 5000 m. The model predicted of the meteotsunami corresponded well with observations.

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JP05h - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami hazards from atypical sources: Examples of the 2020 Samos tsunami and the 2022 Tonga tsunami

DOI: 10.57757/IUGG23-1064 - LINK

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Hazardous tsunamis are generally generated by megathrust earthquakes in subduction zones, like the 2004 Mw 9.1 Sumatra-Andaman earthquake and the 2011 Mw 9.0 Tohoku earthquake. However, recent severe tsunami impacts from atypical sources gain remarkable attention from scientists in related fields. The 2020 Samos normal-faulting earthquake of Mw 6.9 produced an unexpected maximum tsunami runup of up to 3.8 m. The 2022 Hunga Tonga–Hunga Ha'apai volcanic eruption generated unusual tsunami through the air-sea coupling of atmospheric acoustic-gravity waves and ocean surface, which is widely observed in the global oceans. Here, we present the tsunami source characteristics and hydrodynamic behaviours of the two aforementioned atypical cases to investigate the intensifying factor for both tsunami events. We adopt an integrated approach, including source inversion and tsunami modelling, together with spectral and statistical analyses of tsunami waveforms. We find the 2020 Samos tsunami is exacerbated by not only the favorable source conditions for tsunami generation but also the near-source bathymetric morphology. For the 2022 Tonga volcanic tsunami event, we identify four distinct tsunami wave components which are associated with their complex generation mechanisms ranging from air–sea couplings to seafloor crustal deformation during the volcanic eruption. The unexpected tsunami hazards from the atypical sources highlight the significance of various unusual mechanisms for tsunami generation and some favored conditions in intensifying tsunami behaviours. Both tsunami events call for technical improvement for traditional seismic warning system.

References

Hu, G., et al. (2022) https://doi.org/10.1029/2022JB023961

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JS01a - Cryoseismology (IASPEI, IACS, IAG)

Probing the Greenland ice sheet by teleseismic P-wave coda autocorrelation

DOI: 10.57757/IUGG23-1399 - LINK

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[2]University of Kerala, Department of Geology, Thiruvananthapuram- Kerala, India

Seismic body waves from distant earthquakes travel steeply to a seismic station and carry rich information about subsurface structures. In an ice sheet environment, the sharp seismic discontinuity at the ice-bedrock interface effectively reflects the energy that is bounced from the free surface. Thus, the ice sheet acts as a waveguide to trap a large portion of incident seismic energy, resulting in repetitive ground motions recorded by over-ice seismometers. The weak self-similar signals can be amplified by cross-correlating the earthquake seismograms with themselves (i.e., autocorrelation) before stacking over multiple events. Here, we apply this autocorrelation technique to the records of P-wave arrivals and following reverberations (i.e., the P-wave coda) of stations deployed over the central region of the Greenland ice sheet (GrIS), the second-largest ice sheet on Earth. Firstly, we estimate the thickness and P- over S- wave speed ratio of the ice sheet beneath several recording sites and find good agreement with independent estimates primarily based on airborne radio-echo-sounding data.

Furthermore, we observe seasonal fluctuation in amplitudes of P-wave coda autocorrelograms, with stronger reflection peaks in summers and weaker in winters. We use numerical experiments to decipher the mechanism underlying temporal variation. Our findings could shed light on the working mechanisms of the GrIS and similar environments, including future missions to icy planets and satellites.

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JS01a - Cryoseismology (IASPEI, IACS, IAG)

ECS Awardee 2023: Unraveling shallow ice structure with active and passive seismic surveys at west Antarctica

DOI: 10.57757/IUGG23-2409 - [LINK]

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[2]Massachusetts Institute of Technology, Earth- Atmospheric- and Planetary Sciences, Cambridge, USA
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[5]University of Oklahoma, Oklahoma Geological Survey, Norman, USA
[6]University of California- Santa Cruz, Earth & Planetary Sciences Department, Santa Cruz, USA

Seismic signals are powerful to characterize ice and subsurface structures, and we image shallow ice structure near the West Antarctic Ice Sheet (WAIS) Divide with active and passive seismic data and the Thwaites Glacier eastern shear margin with passive data. The eastern shear margin has a planned active-seismic survey in the 23/24 field season. Passively recorded seismic ambient noise can be used to extract wave propagations between receivers and provide complementary information to the active seismic data. High-frequency energy is high in active-seismic data, but surface waves are often more prominent in ambient noise records due to their source mechanisms. We use a surface-wave dispersion analysis, an analysis of horizontal-versus-vertical (H/V) ratio, wave-equation-based seismic imaging, and reflection migration for imaging firn-air, firn and shallow ice layers. We identify the leaky modes following the direct waves by examining their behaviors of energy decay and particle motion. The leaky modes are guided P waves and contain P-wave velocity information and exist possibly due to the sharp velocity contrasts at the firn layer. Together with normal modes, we use a joint inversion of leaky and normal modes for P- and S-wave velocity estimation in the near-surface. Because seismic ambient noise always exists, we also use them for time-lapse analysis of the ice structure for understanding its dynamics.

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JS01a - Cryoseismology (IASPEI, IACS, IAG)

Bayesian surface wave dispersion inversion of glaciated environments

DOI: 10.57757/IUGG23-1912 - LINK

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[1]ETH Zurich, D-ERDW Institute fur Geophysik, Zurich, Switzerland
[2]Icelandic Meteorological Office, Volcanos- earthquakes & deformation, Reykjavik, Iceland
[3]Alfred Wegener Institut, Glaciology, Bremerhaven, Germany
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Institut Terre et Environnement de Strasbourg - UMR7063, Strasbourg, France

We present a probabilistic approach to the inversion of surface wave dispersion data from glacial environments. This is intended to (i) assess non-linearity and non-uniqueness, and (ii) properly quantify resolution and trade-offs. For this, we use seismic data from Distributed Acoustic Sensing (DAS) experiments deployed on the Vatnajökull ice sheet located on Grímsvötn volcano in Iceland, and the Northeast Greenland Ice Stream (NEGIS).

Our method is based on a regularisation-free Bayesian inference approach, implemented using a Hamiltonian Monte Carlo (HMC) algorithm. Exploiting derivative information for efficient sampling of high-dimensional model spaces, HMC approximates the posterior probability densities of all model parameters. Applied specifically to multi-mode surface wave dispersion measurements, HMC yields probabilistic models of 1-D anisotropic stratified media parameterised in terms of the P-wave velocities Vpv and Vph, the S-wave velocities Vsv and Vsh, the anisotropy parameter η, and density ρ.

The benefits of this approach, not only from a glaciological perspective, include regularisation-free estimates of firn and ice properties, models that are not a priori biased by the exclusion of all parameters except S-wave speed, and some level of direct access to the vertical density profile.

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JS01a - Cryoseismology (IASPEI, IACS, IAG)

Azimuthal seismic anisotropy within a tidewater glacier tongue revealed with array cross-correlation

DOI: 10.57757/IUGG23-4170 - LINK

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Near-terminus areas of glaciers generate a rich spectrum of complex seismicity. Both ballistic and scattered coda waves of seismic events (e.g. surface and basal icequakes, iceberg detachment) carry information about elastic wave propagation within the glacier and, therefore, the mechanical properties of the ice. In this study, we utilize a temporary array deployment to obtain insights into cryoseismicity and ice structure of the Hans glacier at Hornsund, Svalbard.

We use direct and scattered wave fields from tens of thousands of icequake records to reconstruct the impulse response between seismometer pairs within the array and to infer Rayleigh wave velocities. The dynamic ice deformation around the array results in good azimuthal coverage. We demonstrate, that misfits between azimuthally bin-averaged zero-lags of cross-correlations and a theoretical sinusoidal dependence of apparent velocity can be used to measure an azimuthal anisotropy of the glacial ice, 3.5% in our case. We suggest that the anisotropy is a result of stress regime and crevassing. The study thus shows how passive seismic records can be used to characterize terminus regions near the ice-ocean boundary. In future experiments, this may help elucidate how ice dynamics precondition iceberg calving, one of the central processes of ice mass loss and eustatic sea level rise.

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JS01a - Cryoseismology (IASPEI, IACS, IAG)

Seasonal observations of the ocean and sea ice environment offshore Oliktok Point, Alaska, using distributed acoustic sensing

DOI: 10.57757/IUGG23-1121 - LINK

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We present new results from a multiyear effort to record environmental signals in the Beaufort Sea using distributed acoustic sensing (DAS). We collected seafloor DAS data on a 36-km long segment of telecom dark fiber for eight one-week intervals in 2021 and 2022. The eight data collects comprise two samplings of each Arctic "season" (ice bound, ice free, and partial ice coverage during freezing and breakup). We recorded icequakes, floating sea-ice collisions, ice grounding events, ice flexural-gravity waves excited by winds, currents, and hovercrafts, ocean gravity waves, earth microseisms, and submarine soil/permafrost resonance. We have used these signals to characterize both sea ice extent and sea-ice thickness in the Beaufort Sea. Sea ice-extent is determined by clustering ambient noise data in 30-minute windows using a convolutional neural network. The presence or absence of ocean gravity waves is the dominant factor in the ice/no-ice clustering. Sea ice thickness is estimated from the inversion of ice flexural-gravity wave dispersion curves. This novel application has the added benefit of simultaneously inverting for snow thickness on the ice sheet, a confounding factor in other remote sensing methods. Ocean gravity wave parameters will also be presented. Comparison with wave buoys purposefully deployed above the fiber indicates that DAS can capture low-frequency waves with high spatial resolution during both open water and partially ice-covered periods. *SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525*

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JS01a - Cryoseismology (IASPEI, IACS, IAG)

Seismic emissions and frostquakes: mechanisms of thermal stress release during seasonal freezing and melting of soft soils in subarctic areas

DOI: 10.57757/IUGG23-1517 - LINK

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In this study the analysis of continuous seismic data is used to investigate the processes related to seismic events generated through the release of accumulated thermal stresses in the upper water-saturated soils during freezing and melting. Under certain conditions, the stresses are released as a swarm of small-scale magnitude impulses, called cryoseismic emission, which have no or very little effect on the infrastructures. In some cases, however, this stress release can result in seismic events called frostquakes. Such events can be of relatively large magnitude, and they are capable to produce cracks on the ground surface and damage infrastructures such as buildings and roads. To understand what combinations of weather and ground conditions results in these different stress release mechanisms, we installed two seismic arrays with co-located soil stations in two geographically different sites in Northern Finland characterized by different weather, geological and hydrogeological conditions. The first site is located in the municipality of Sodankylä at the latitude of 67.36 deg. and the second one in the city of Oulu at the latitude of 65.04 deg. Based on local inhabitants 'eyewitness' reports of ground shaking and unusual 'seismic noise' near the Oulu site on 06.01.2023, we identified several frostquakes in seismic records. The analysis of continuous seismic records allowed us to recognise two different stress release mechanisms: frostquakes and cryoseismic emission. Our results support the conclusion that stress release by different mechanisms is defined mainly by certain meteorological and groundwater conditions.

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JS01b - Cryoseismology (IASPEI, IACS, IAG)

Seismogenic glacier sliding

DOI: 10.57757/IUGG23-0584 - LINK

Fabian Walter[1]
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Already some of the earliest cryoseismological studies aimed at detecting signals describing glacier sliding. However, for decades the existence of widespread stick-slip icequakes was debated as most microseismic monitoring networks failed to provide clear evidence for seismogenesis below the surface crevassing zone. In recent years, studies have shown that stick-slip signals accompany rapid sliding of polar ice streams as well as relatively slow motion of mountain glaciers.

Here I review recent observations of stick-slip sliding monitored with seismic instruments. Sustained series of stick-slip ruptures seem to be a common manifestation of surging motion and these tremor-like signals lasting up to several hours have counterparts in volcanic and tectonic environments. I discuss under which conditions such seismogenic stick-slip sliding seems to emerge in a noisy glacier environment and why it is easily missed with local seismic networks. Simplified slider-block models show how stick-slip tremor accompanies water-enhanced sliding episodes assuming that glacier sliding can be described by rate-and-state friction. This friction rheology explains the complex dynamics of tectonic boundaries including earthquake rupture and triggering. Accordingly, first applications of finite fault models support the idea of rate weakening bed patches acting as seismic sources embedded within a surrounding rate strengthening ice-bed interface.

Together with stick-slip icequakes, other passive seismic observations hint towards a pervasive hydraulic control on basal sliding and fracturing. A better understanding of seismic sources and wave propagation related to glacier ice could therefore be key in addressing critical knowledge gaps in subglacial processes.

Already some of the earliest cryoseismological studies aimed at detecting signals describing glacier sliding. However, for decades the existence of widespread stick-slip icequakes was debated as most microseismic monitoring networks failed to provide clear evidence for seismogenesis below the surface crevassing zone. In recent years, studies have shown that stick-slip signals accompany rapid sliding of polar ice streams as well as relatively slow motion of mountain glaciers.

Here I review recent observations of stick-slip sliding monitored with seismic instruments. Sustained series of stick-slip ruptures seem to be a common manifestation of surging motion and these tremor-like signals lasting up to several hours have counterparts in volcanic and tectonic environments. I discuss under which conditions such seismogenic stick-slip sliding seems to emerge in a noisy glacier environment and why it is easily missed with local seismic networks. Simplified slider-block models show how stick-slip tremor accompanies water-enhanced sliding episodes assuming that glacier sliding can be described by rate-and-state friction. This friction rheology explains the complex dynamics of tectonic boundaries including

earthquake rupture and triggering. Accordingly, first applications of finite fault models support the idea of rate weakening bed patches acting as seismic sources embedded within a surrounding rate strengthening ice-bed interface.

Together with stick-slip icequakes, other passive seismic observations hint towards a pervasive hydraulic control on basal sliding and fracturing. A better understanding of seismic sources and wave propagation related to glacier ice could therefore be key in addressing critical knowledge gaps in subglacial processes.

JS01b - Cryoseismology (IASPEI, IACS, IAG)

Study of the structural and dynamic changes of a surging glacier using seismic observations

DOI: 10.57757/IUGG23-1567 - LINK

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Glacier flow instabilities are mainly caused by changes at the ice-bed interface, where basal slip and sediment deformation drive basal glacier movement. Understanding basal processes and their response to external forcing remains difficult due to limited access to the glacier bed. In this study, we examine variations in subsurface and subglacial mechanical conditions of Kongsvegen glacier (Svalbard). This glacier shows strong indications of an imminent new rapid flow event. To investigate the potential causes of such an acceleration, we combine conventional measurements such as surface velocity (20 GNSS along the flow line) and basal water pressure (two boreholes) with seismic measurements (14 seismometers along the flow line and 6 seismometers in boreholes) and a unique measurement of basal drag applied to the sediments. We use our seismic measurements to study (1) subglacial hydrological conditions and (2) changes in ice structure using seismic interferometry.
At seasonal time scales, we observe an inverse relationship between basal drag and surface runoff. At shorter time scales, the basal drag is initially very sensitive to meltwater input, but this sensitivity gradually decreases and almost disappears as the season progresses. The response of the glacier to meltwater inflow often reflects transient flow behaviour. In winter, we observe a doubling of the basal drag compared to the previous winter. These changes are concomitant with changes in seismic velocity suggesting a downward propagation of the surge. Using our multi-instrument approach, we discuss the different behaviours observed during two years of recordings to highlight the mechanisms of glacier destabilisation.

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JS01b - Cryoseismology (IASPEI, IACS, IAG)

On-ice seismicity of a rapidly-rising jökulhlaup cycle at the A.P. Olsen Ice Cap, NE-Greenland

DOI: 10.57757/IUGG23-4316 - LINK

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Rapidly-rising jökulhlaups, or glacial lake outburst floods, are a phenomenon with a high potential for damage. The initiation and propagation processes of a rapidly-rising jökulhlaup are still not fully understood. Seismic monitoring can contribute to an improved process understanding, but comprehensive long-term seismic monitoring campaigns capturing the dynamics of a rapidly-rising jökulhlaup are rare. In 2012, we installed a seismic network at the marginal, ice-dammed lake of the A.P. Olsen Ice Cap in NE-Greenland. Episodic outbursts from the lake cause flood waves in the Zackenberg river, characterized by a rapid discharge increase within a few hours. We deployed industrial geophones (4.5 Hz) for the five on-ice stations. Two stations were designed as mini-arrays with three vertical sensors, and the remaining ones were equipped with three-component sensors. All sensors were sunk about 3 m into the ice. Our 6 months long seismic dataset comprises the whole fill-and-drain cycle of the ice-dammed lake in 2012 and includes one of the most destructive floods recorded so far for the Zackenberg river. Seismic event detection reveals periods of high seismicity during enhanced surface melting prior to the outburst flood. During the outburst itself the number of detected events dropped due to the elevated seismic tremor level. Based on waveform characteristics and event localization we detected potential basal events. We will present and discuss the temporal and spatial evolution of basal events throughout the entire fill-and-drain cycle of the jökulhlaup.

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JS01b - Cryoseismology (IASPEI, IACS, IAG)

Array seismologic insights into Grímsvötn jökulhlaups, Iceland

DOI: 10.57757/IUGG23-4481 - LINK

Thoralf Dietrich[1], Eva P. S. Eibl[1], Finnur Pálsson[2], Eyjólfur Magnússon[2], Bergur H. Bergsson[3], Daniel Vollmer[1], Sebastian Heimann[1], Fabian Lindner[4], Daniel Binder[1], Sigrid Roessner[5]
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Jökulhlaups (also known as GLOF, glacier lake outburst floods) that travel subglacially are only detectable indirectly, via observation of the glacier's surface deformation (GNSS, InSAR) or the seismic signals they generate.
At Iceland's Vatnajökull glacier, floods from Grímsvötn travel more than 40km below the ice before feeding into the glacial river.
To study the propagation and the physics of the jökulhlaups, temporal seismic arrays were installed close to the terminus, i.e. west, southwest and south of Vatnajökull. Frequency-wavenumber-analysis (fk-analysis) and match field processing (MFP) are two seismic methods able to locate the generated tremor along the propagation path. We present insights into Grímsvötn floods between 2014-2016 and October 2022. We discuss the properties of the 3-component seismic data and their location with respect to hydrometric and GNSS observations. Ultimately, these understandings may contribute to improve the early warning of subglacial floods.

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JS02a - Seismo – Geodesy (IASPEI, IAG)

What have we learned about the earthquake deformation cycle from advances in geodetic monitoring?

DOI: 10.57757/IUGG23-1599 - LINK

Tim Wright[1]
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Over the last 20 years, measuring Earth's deformation with satellite geodesy has developed from a niche research activity into a robust and reliable operational suite of monitoring tools. We now have thousands of continuously recording GNSS stations and a suite of satellites acquiring data suitable for routine InSAR analysis. In this presentation, I will review what we have learned from these data sets about the earthquake deformation cycle and discuss the areas where further research is needed. Before satellite geodesy, coseismic deformation had been measured for just a handful of earthquakes. We have now mapped the deformation fields from hundreds of events, and InSAR, in particular, has been particularly powerful, revealing a diverse array of behaviour in the brittle crust. Following earthquakes, we have now built up long time series of post-seismic observations for many events. The combination of spatial and temporal information that satellite geodesy provides is being used to disentangle the mechanisms responsible for postseismic stress adjustments, in turn giving us unique insights into the rheology of the crust and mantle. Once initial rapid postseismic transients have decayed, long-term geodetic observations from InSAR and GNSS are now mapping strain accumulation patterns over vast regions, and these are beginning to be used to help better inform seismic hazard models. We are also increasingly seeing a variety of transient behaviours that don't fit into the classic co- post- inter-seismic framework. I will end the presentation by discussing these and the potential for new discoveries over the coming decade.

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JS02a - Seismo – Geodesy (IASPEI, IAG)

Probing the locking status of the Xianshuihe fault with geodetic observations and a viscoelastic deformation model

DOI: 10.57757/IUGG23-2485 - LINK

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The slip rate and locking status of active faults are important for regional seismic hazard assessments. Up to now, elastic models have been routinely used in probing the fault locking status with geodetic observations. The viscoelastic deformation, however, was suggested to be of significance for estimating the fault locking status. In this study, we examined the effect of viscoelastic deformation for mapping the fault locking by applying both elastic and viscoelastic deformation models on the Xianshuihe fault, a major seismogenic fault in southwestern China. In the past 500 years, the Xianshuihe fault has experienced 19 earthquakes with M>6, making it a cause for common concern of seismic hazard among both scientific and societal communities. We constructed viscoelastic deformation models based on GPS velocities near the Xianshuihe fault to invert the fault locking status of this fault. Our results suggest that elastic models result in overestimates of both the fault locking depth and moment accumulation rate, while viscoelastic deformation models yield more reliable results. Relying on the obtained fault locking distribution, we identify four potential asperities along the Xianshuihe fault. And, a clear spatial correlation between the asperities and historical ruptures was observed, suggesting that the fault locking may control the rupture extent of strong earthquakes on this fault. Moreover, we found that the 2022 M6.8 Luding earthquake only ruptured a part of an identified asperity. And the seismic moment accumulated on the unruptured segment is roughly equivalent to an Mw6.8 earthquake, underscoring the potential seismic hazard there.

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JS02a - Seismo – Geodesy (IASPEI, IAG)

Contemporary crustal deformation on the borderland between China and Myanmar illuminated by GPS measurements

DOI: 10.57757/IUGG23-0213 - LINK

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The borderland between China and Myanmar is characterized by complex tectonics and heavy seismic hazard, but its present-day crustal deformation pattern is still contentious. We have processed all the data of regional GNSS networks from 1998 to 2020 for this region and further derived strain rate fields. The results show that Myanmar arc moves towards the Qinghai Tibet Plateau in the NNE direction at a velocity of ~30mm/yr. The shear strain accumulation in this zone is prominent, with east-west compression at outer flank of the arc, and nearly south-north compression at its interior. The Sagaing fault is characterized by heterogeneous kinematics with higher principal strain rate and shear strain rate.Sichuan Yunnan block is rotating remarkably clockwise around the eastern Himalayan syntaxis. The Xiaojiang fault zone is experiencing sinistral strike slip. The central segment of Honghe fault has a lower strike slip rate, while the north and south segments have a relatively higher shear rate. The Dayingjiang fault in southwestern Yunnan shows east-west extension and sinistral strike slip. The Longling-Ruili fault is characterized by dextral strike slip and extension. The NE trending Nantinghe fault, Menglian fault and Jinghong-Daluo fault have lower shear rates, dominated by left-lateral strike- slip. The Lancang fault and Wuliangshan faults are characterized by a dextral strike slip, while the northwest trending Longling-Lancang fault zone shows dextral strike slip and tension. The study is significant to earthquake disaster assessment and understanding of the regional geodynamics of this region.

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JS02a - Seismo – Geodesy (IASPEI, IAG)

Crustal strain rate field around Izu collision zone, Japan, inferred from GNSS and InSAR data

DOI: 10.57757/IUGG23-0045 - LINK

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The Izu collision zone, characterized by the collision between the Izu-Bonin arc and the Honshu arc, is located in the northernmost part of the Philippine Sea Plate. Numerous large earthquakes have occurred throughout history, particularly in the northeastern margin of the zone (Ishibashi, 2004, Earth Planets and Space). From our previous analysis result using GNSS, a shear deformation zone, whose width is about 20 km in EW, exists in the northeastern part of the Izu Peninsula (Doke et al., 2020, Geological Society of London, Special Publications). However, GNSS station density is still insufficient to understand this complex tectonic field.

In this study, we performed GNSS and InSAR analysis to estimate the crustal strain rate field in and around the Izu collision zone. To calculate the high-resolved strain field, we combined E-W components obtained from the 2.5-D analysis result of InSAR time series analysis of ALOS-2/PALSAR-2 data and N-S components of GNSS velocity data that were spatially interpolated.

The estimated crustal strain rate field, whose output resolution is 100 m, shows not a homogeneous deformation zone but the existence of some patch-like deformation concentrated zones. Some of the deformation zones may be related to the volcanic activities in this region (Hakone and Higashi-Izu volcanoes). The other deformation zones spatially correspond well with the branch faults of the active Kita-Izu fault zone, which is the source fault of the 1930 Kita-Izu earthquake (M7.0). Therefore, this result shows the strain concentrations and possibilities of earthquake occurrences on these branch faults.

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JS02a - Seismo – Geodesy (IASPEI, IAG)

Kinematic of the Maghrebian Thrust Belt and the Eu-Nu convergence in North Africa

DOI: 10.57757/IUGG23-4866 - LINK

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[2]Institut National de Cartographie et Télédétection, Geodesy Department, Algiers, Algeria
[3]National Research Institute of Astronomy and Geophysics, Geodynamics Department, Cairo, Egypt
[4]Université Science et Technologie Houari Boumediene, Faculté des Sciences de la Terre, Bab-Ezzouar- Algiers, Algeria

The Maghrebian Atlas Mountains in North Africa results from the Nubia – Eurasia (Nu-Eu) plate convergence in the western Mediterranean. In this study, we examine the correlation between the thrust belt and adjacent Sahara Platform domains in the light of new GPS and seismotectonic results. We also test the Quaternary tectonics and seismotectonic activity from the GPS velocities and determine 3 – 6 mm/yr oblique convergence with transpression and block rotations. The diffuse Nu-Eu plate boundary originally limited to the North Africa coastline extends further south to include the Maghrebides tectonic blocks and southern Sahara Atlas suture zone, the Rif and Tell Atlas, Middle Atlas, High Plateau, and High and Sahara Atlas. The kinematics and late Quaternary strain distribution show westward anticlockwise rotations with an average 3°/Myr from NNW-SSW to WNW-ESE. The transpressive tectonic system is also conducted by large East-West trending right-lateral shear zones inducing clockwise rotation on regional tectonic blocks consistent with paleomagnetic results along the Tell Atlas. The crustal deformation is documented along the tectonic blocks of the Atlas Mountains and Sahara Platform pointing out large earthquakes and the displacement field with strain partitioning largely controlled by the Nu-Eu plate motions.

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JS02b - Seismo – Geodesy (IASPEI, IAG)

Geodetic exploration of elastic/inelastic behavior of the Earth's crust with time-dependent deformation

DOI: 10.57757/IUGG23-0772 - LINK

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Crustal deformation is analyzed assuming an elastic medium in most cases. However, inelastic deformation plays an important role in various crustal processes such as tectonic stress accumulation and long-term topographic formation. We have been trying to isolate inelastic deformation signals from geodetic observation data. The M9.0 2011 Tohoku earthquake has brought a unique opportunity in this regard. The postseismic deformation pattern was reversed from the interseismic one. However, along the concentrated contraction zone along the Japan Sea coast, we identified persistent localized contraction before and after the Tohoku earthquake, which is considered to be an inelastic contribution. The identified inelastic strain rate is consistent with the geologically estimated value, indicating a contribution of inelastic processes to long-term deformation. Associated with the Tohoku earthquake, crustal deformation of the Japan island arc has been time-dependent. Since the strain components change in time satisfying the stress equilibrium, time-dependent strain rate data allows us to estimate the heterogeneous distribution of elastic properties and inelastic contribution. Also, we can assume that the observed strain can be considered a sum of elastic and inelastic strains. By assuming the plane stress condition, elastic deformation of the crust can be predicted with an appropriate boundary condition. Then the residuals can be considered inelastic contributions. We will present an overview of these approaches and their applications to GNSS data in Japan to demonstrate how the exploration works, together with their tectonic implications.

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JS02b - Seismo – Geodesy (IASPEI, IAG)

Transient deformation associated with an earthquake swarm in the Noto Peninsula based on combined analysis of multiple GNSS observation networks

DOI: 10.57757/IUGG23-0754 - [LINK]

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An extensive seismic swarm, as well as transient deformation, have continued since the end of November 2020 in the Noto Peninsula, central Japan, which is a non-volcanic/geothermal area far from the major plate boundaries. We present the transient deformation clarified from a combined analysis of multiple GNSS observation networks, seismicity, and their interpretation. We analyzed data at 30 continuous GNSS stations operated by SoftBank Corp., the Geospatial Information Authority of Japan (GSI), and universities. The total displacement pattern for two years shows horizontal inflation and uplift up to ~70 mm around the source of the earthquake swarm. In the first three months, the opening of the low-angle tensile crack is estimated with a volumetric increase of ~1.4 x 10^7 m^3 at a depth of ~16 km. In the next 15 months, the observed deformation is well reproduced by shear-tensile sources, which suggests an aseismic reverse-type slip and expansion of a southeast-dipping fault zone at a depth of 14-16 km. The estimated shear-tensile sources locate at the downdip of the clusters of the earthquake swarm. We interpreted our deformation model and earthquake sequence as follows. Upwelling fluid sub-horizontally spread in a southeast-dipping fault zone. And they migrated up-dip along the fault zone and caused sub-meter aseismic slip below the seismogenic depth. The aseismic slip further triggered intensive earthquakes above the seismogenic depth.

Acknowledgments: We are grateful to SoftBank Corp., ALES Corp., and GSI for providing us with GNSS observation data. This work was supported by JSPS KAKENHI Grant Number JP22K19949.

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JS02b - Seismo – Geodesy (IASPEI, IAG)

Discriminating between tectonic transients and processing artifacts in GNSS displacement time series: A case study from the Cascadia subduction margin

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Throughout the earthquake cycle at fault zones, Earth's crust undergoes deformations. GNSS coordinate time series reveals tectonic motion, seismic displacements, and periodic signatures. Additional motion patterns are usually summarized as transient tectonic signals, i.e., unexpected accelerations with respect to standard trajectory models. As the number of permanent stations increases and as time series grow, we are increasingly able to recognize transient tectonic signals. Since some of these suspected tectonic transients have subtle magnitudes or sometimes unusual spatiotemporal features, we need to develop methods for determining which transients are artifacts and which are of a tectonic origin.

Here, we investigate the impact of certain GNSS processing choices and how they affect the appearance of transients in the GNSS displacement time series solutions. In our study, we choose data from Cascadia, a region for which the occurrence of transients in the GNSS time series is well known. To control our database, we processed data based on network solutions from 150 carefully selected GNSS stations for the time between 2015 and 2020. Then, we have an opportunity to discriminate between tectonic transients and processing artifacts in the GNSS displacement time series. We will discuss the detected transients against selected GNSS-related indicators (data quality, observation residuals, troposphere delays, etc.) to identify potential GNSS artifacts aliasing into the transient signals.

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JS02b - Seismo – Geodesy (IASPEI, IAG)

Slow slip events on la Venta-Chacalapa fault system, Mexico

DOI: 10.57757/IUGG23-1146 - LINK

Vladimir Kostoglodov[1], Victor Cruz-Atienza[1], Ekaterina Kazachkina[1], Jose Antonio Santiago[1], Jorge Real[1]
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La Venta-Chacalapa creeping fault system (LVC) is the ~650 km long northern boundary of the Xolapa sliver, which is located along the Pacific coast of Guerrero and Oaxaca states of Mexico. The LVC splits the North America tectonic plate (NA) and the Xolapa sliver, which is slowly moving SE with respect to (wrt) the NA with an average secular rate of ~5 mm/year as a consequence of the oblique subduction between the Cocos and NA plates.
Long-term GPS observations unveil transient episodes of crustal slow slip events (cSSE) on the LVC. These cSSE are concomitant with large subduction thrust slow slip events (tSSE) which had been occurring in Guerrero every 3.5-4 years before 2017, and about of ~1 year after 2017 on the plate interface between the Cocos and NA plates. The tSSEs apparently reduce the normal stress and the friction on the LVC, thereby activating the cSSEs.
The SE component of Xolapa displacements on the LVC during the cSSEs had developed with a time delay (~3 month) wrt the trench normal displacement component. After the great Mw8.2, 2017, Chiapas earthquake the frequency of tSSEs have increased while the time lag has almost vanished. Very short time lags were also detected on the LVC in Oaxaca where the frequency of tSSE is of 1-2 years.
Our observations of cSSEs on the LVC are in general consistent with the 'Rate and State Friction' theoretical and experimental results (e.g., Boettcher and Maron, 2004).

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JS02b - Seismo – Geodesy (IASPEI, IAG)

Geodetic and geological investigation of interseismic deformation onshore Paliki peninsula, Cephalonia, Greece

DOI: 10.57757/IUGG23-3610 - LINK

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[1]National Observatory of Athens, Institute of Geodynamics, Athens, Greece
[2]University of Patras, Department of Geology, Patras, Greece
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Department of Geology and Geoenvironment, Athens, Greece

We present a comprehensive analysis of geodetic data, including InSAR imagery and GNSS observations, to assess the pattern of ground motions of the Paliki peninsula in western Cephalonia, Greece. Paliki is prone to frequent, strong earthquakes, due to its close proximity to the right-lateral Cephalonia Transform Fault (CTF), a 140 km long strike-slip fault that accommodates the relative motion between the Apulian and Aegean lithospheric plates. Our analysis covers the period from 2016 to 2022 and leverages the LiCSBAS, an open-source package, for InSAR time series analysis with the N-SBAS method. We combined the InSAR results with the GNSS observations. The results indicate that active faults on the Paliki peninsula are oriented approximately N-S and exhibit slip rates between 2-5 mm/yr in the line-of-sight direction. The horizontal component of movement is dominant, providing initial evidence of right-lateral strike-slip faulting on the peninsula. The InSAR data also indicate possible post-seismic motion along the fault plane that ruptured on the 3 February 2014 M5.9 earthquake in the northwest part of the peninsula. Moreover, we have identified other possible active structures, including both strike-slip and thrust faults, confirmed by field geological data. The coastal town of Lixouri undergoes uplift, as evidenced by positive line-of-sight displacement values in both imaging geometries. Velocity cross-sections reveal several discontinuities, possibly bounded by active faults and/or crustal flexure. The integration of geodetic data with seismological and field geological data provides a valuable tool for the monitoring of interseismic behaviour of active faults.

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JS02c - Seismo – Geodesy (IASPEI, IAG)

20 years slip history at the La Plata Island subduction segment, Central Ecuador

DOI: 10.57757/IUGG23-1068 - LINK

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[2]Escuela Politecnica Nacional, Instituto Geofisico, Quito, Ecuador

The La Plata subduction segment in Central Ecuador is a 50x50 km2, shallow isolated asperity hosting regular Slow Slip Events (SSEs) and seismic swarms. Here, we combine 20 years of seismological and geodetic data to document the history of slip deficit accumulation and its release. Inter-SSEs slip deficit geodetic model reveals that the plate interface appears to be fully locked from the trench down to 15 km depth over a length of 70 km along trench. Analysis of survey-mode GNSS data reveals that a large SSE with equivalent magnitude of Mw 7.2 ruptured the full locked area in 2005. This SSE was synchronous to a large seismic swarm that lasted ~2.5 months, included several M~6 earthquakes, and accounting for 10-15% of the total moment release. Two large SSEs with magnitude of Mw 6.8-6.9 then occurred in 2016 and 2021, rupturing the shallowest part of the locked area. Kinematic slip inversions reveal thatthe 2016 & 2021 SSEs propagated from north to south. Aside the large SSEs, several smaller (Mw 6-6.3) and shorter SSEs occurred in 2010, 2013, 2017 and 2019, involving partial ruptures of the locked patch. All occurred synchronously to seismic swarm. This history allows to provide the evolution of moment accumulation and release through time. It shows that the behavior of the asperity is neither time-predictable nor slip-predictable.

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JS02c - Seismo – Geodesy (IASPEI, IAG)

Observation of seafloor strain caused by shallow SSE and VLFE fault in the Nankai Trough by seafloor fiber optic strainmeters.

DOI: 10.57757/IUGG23-2395 - LINK

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[2]Scripps Institution of Oceanography, Institute of Geophysics and Planetary Physics, San Diego, USA

Slow slip occurs repeatedly in the shallow part of the plate subduction boundary region in the Nankai Trough (Araki et al., 2017). To investigate its activity in wider area, we developed and installed a seafloor fiber-optic strainmeter connected to a submarine cable observation network (DONET) in west of the previous observation network in the borehole in 2019. In January-February, 2022, the seafloor fiber-optic strainmeter observed slow transient extension of about 0.7 μstrain over 3 weeks. Very low-frequency earthquakes (VLFEs) were observed in the vicinity during this period. The fiber-optic strainmeter was able to observe slow step-like changes for many of the VLFEs that occurred near the strainmeter. We observed strain change about 20 n strain for a VLFE of Mw 4.4. The observed strain change polarity and transitions were consistent with those expected from the focal mechanisms of the VLFEs, suggesting the possibility to investigate slip processes of each individual VLFE by seafloor fiber strain record.

The strain changes by the local VLFEs were insufficient to account for the total slow 3-week strain change observed by the fiber optic strainmeter. Therefore, we propose that shallow slow slip occurred in the areas where the VLFEs were observed, and that the slow slip may have loaded individual VLFE faults into a burst-like cluster of VLFEs.

We further expanded our strainmeter observations by adding two strainmeters in array and in different direction in November 2022, where we anticipate more robust and detailed fault slip analysis will be performed in the next similar slip occurrence.

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JS02c - Seismo – Geodesy (IASPEI, IAG)

Evaluating high-rate positioning quality of a heterogeneous network of low-cost GNSS receivers

DOI: 10.57757/IUGG23-4295 - LINK

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High-rate positioning from Global Navigation Satellite Systems (GNSS) observations involves the acquisition of signals at a higher rate (> 1 Hz) than conventional positioning (< 0.7 Hz). This increased measurement frequency has opened possibilities for a wide range of applications, such as measuring seismic waves and monitoring tsunamis, volcanoes, and landslides. The development of low-cost GNSS receivers has made high-rate positioning more accessible and affordable for a wide range of applications. However, the performance of these low-cost GNSS receivers for high-rate measurement applications still needs to be thoroughly evaluated and analyzed to ensure their reliability and accuracy. To investigate the reliability and accuracy of low-cost GNSS receivers for high-rate positioning, we collect 6-day continuous data at 1-Hz, 2-Hz, 5-Hz, and 10-Hz frequencies from a heterogeneous network of stations equipped with geodetic, survey-grade, and navigation antennas. These stations comprise of dual (u-blox ZF9P) and single frequency (u-blox M8T) low-cost GNSS receivers. In this study, we evaluate these sets of high-rate data by comparing signal-to-noise ratio (SNR), cycle slip, dilution of precision, multipath, and precise point positioning. In addition, we assess the effects of the ultra-rapid and final precise orbit product on the PPP solutions.

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JS02c - Seismo – Geodesy (IASPEI, IAG)

Analysis of the dynamical displacement observed on GNSS stations in Greece due to the 06/02/2023 southern Turkey earthquakes.

DOI: 10.57757/IUGG23-2081 - LINK

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This work presents an analysis of dynamic displacements observed on GNSS stations in the Aegean region, induced by the two earthquakes with magnitude 7.8 and 7.5, in Southern Turkey on 06/02/2023. For this reason, GNSS data of 1Hz observation rate from continuously operating stations located across the Aegean Sea and the mainland of Greece was processed using Precise Point Positioning method. Position time-series were analyzed to estimate the amplitude of the displacement, the direction in which the maximum displacement is observed and the time of occurrence. Furthermore, emphasis is given on comparing the characteristics of the displacements observed between the two events and examine a possible correlation with the corresponding faults' geometry for each separate event. An additional evaluation of the kinematic behavior of permanent GNSS stations located in proximity of the Hellenic subduction zone with the African plate, the latter sharing a tectonic boundary with both the Arabian and Anatolian plates was conducted. The results of this work discuss the effects that strong earthquakes can have at distances over 1000 km and along active tectonic boundaries, implying the larger-scale impact of such geohazards.

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JS02c - Seismo – Geodesy (IASPEI, IAG)

Anthropogenic earthquakes monitoring with high-rate GNSS: Event detection and focal mechanism determination

DOI: 10.57757/IUGG23-0666 - LINK

Iwona Kudłacik[1], *Anna Tymińska*[2], *Jan Kapłon*[1], *Grzegorz Lizurek*[2], *Marco Fortunato*[3], *Kamil Kaźmierski*[1], *Mattia Crespi*[3]
[1]*Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Wrocław, Poland*
[2]*Institute of Geophysics Polish Academy of Sciences, Department of Seismology, Warszawa, Poland*
[3]*DICEA-Sapienza University of Rome, Geodesy and Geomatics Division, Rome, Italy*

Anthropogenic earthquakes are rarely monitored with high-rate GNSS. Nevertheless, the progress in the GNSS processing techniques allows recording the mining tremors of smaller amplitudes, i.e., magnitudes about 4, with high-rate GNSS as well as complementary sensors to the seismic instruments. Although high-rate GNSS recording frequency and sensitivity are lower than seismic sensors, high-rate GNSS can capture the waveforms appropriately.

Here we demonstrate that if the GNSS observations are carefully filtered, we can retrieve the small signal of ground vibrations of the low-magnitude shallow anthropogenic earthquakes with the accuracy of very few millimetres for displacements and 1-2 cm/s for velocities. We analysed five mining tremors with magnitudes of 3.4-4.0 and presented the results from high-rate GNSS position changes calculated parallel with the PPP and variometric approach. We obtained satisfying correlations with seismological data in correlation, peak values comparison and earthquake first epoch determination.

Moreover, we show that high-rate GNSS can be a supplementary tool for seismic moment tensor inversion for small magnitude shallow anthropogenic earthquakes and might be crucial in case of a lack of seismic data, complementing unfavourable focal coverage. The obtained full, deviatoric, and double-couple solutions are similar, which shows that GNSS data may be added for moment tensor inversion in place of seismometers if needed without significant loss of the solution quality.

Finally, considering the high-rate GNSS positioning noise level, we demonstrate the capacity to resolve the dynamic displacements from high-rate GNSS at the epicentral distance of about 7-8 km.

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JS03a - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

MT array investigations in the orogenic belts of southeastern Brazil

DOI: 10.57757/IUGG23-1828 - LINK

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A magnetotelluric (MT) regional investigation is underway in Southeastern Brazil as part of a comprehensive Multiphysics project (sponsored by Petronas Brasil) which integrates multiple geophysical datasets aiming to understand the deep structure and tectonic processes connecting onshore orogenic belts and the offshore extended margin that resulted in the formation of the petroliferous Campos basin. The megastructures of the São Francisco Craton (SFC), the Ribeira Fold Belt (RFB) and the basement of Campos basin have been surveyed by a total of 100 broadband and long period MT stations recording at periodicities of 10^{-3} to 10^{5} s, with spacing varying from 25 to 45 km and distributed in a 400 km x 350 km sided NW-SE oriented array. The MT time series were processed using robust methods followed by dimensionality analyses using the phase tensor scheme which pointed to a predominantly three-dimensional character of the study area. The first 3D resistivity models have been derived from non-linear regularized inversion using the full impedance tensor data. The 3D model shows good data fit depicting prominent geoelectric signatures in the suture zone between the CSF and the RFB. There are noticeable variations between the crust and the lithospheric mantle, and good opportunities for the understanding the compartmentalization of the internal domains of the RFB consistent with surface geology. The work is in progress, and the next steps will include recording new MT stations to extend the study area and the integration of results with both onshore and offshore geothermal, gravimetric and magnetic datasets.

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stations to extend the study area and the integration of results with both onshore and offshore geothermal, gravimetric and magnetic datasets.

JS03a - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

3D magnetotelluric imaging of land and amphibious data to understand onshore-offshore lithospheric structure of Southeastern Brazil: A pilot study

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How the lithospheric structure of the coast-parallel orogenic belts in SE Brazil is related to the petroliferous offshore rifted margin is not well understood. We present a three-dimensional magnetotelluric (MT) resistivity model of the Southeastern Brazilian onshore-offshore margin from 174 long period and broadband amphibious MT soundings distributed in NW-SE profiles crossing orthogonally the regional coast-parallel Serra da Mantiqueira and Serra do Mar mountain belts. Dimensionality analysis from phase tensor (PT) along the two main profiles outline the character of the subsurface: i) Onshore, there is a marked three-dimensional behavior with spatially changes over Brasília (BrB) and Ribeira (ROB) Orogenic belts and the PT minimum phase varies over the periods suggesting segmentation in the crust and between the crust and mantle.; ii) Offshore, PT ellipses are mostly 1-D in nature for shorter periods with high minimum phases corresponding to thick conductive sediments in the Santos basin and low minimum phases marking the resistive basement. We undertook 3D inversion of the data incorporating topography/bathymetry. 3-D MT resistivity model shows a highly heterogeneous crust beneath the BrB and a major sub-lithospheric suture zone beneath ROB. Crustal conductivity anomalies distinguish a wide antiformal structure below the BrB and a megasynform structure below the ROB, which provide evidence for both compressional and extensional tectonic regimes beneath the Southeast Brazil.

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Lithospheric structure of Parnaiba basin and Borborema Province examined by a long period magnetotelluric array

DOI: 10.57757/IUGG23-1236 - [LINK]

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An array using *76* long period magnetotelluric (LMT) stations with 70 km spacing was deployed covering central and northeast sector of Parnaiba basin and the west edge of the Borborema Province in northeast Brazil. The data were processed including the remote reference technique to improve the estimated transfer functions – Full impedance tensor (Z) and Tipper (T) data spanning from 10s to over 10,000 s. 3D MT inversion tests using ModEM code were carried out using best practice procedures and good misfits have been achieved e.g., nRMS ~ 2.2 for joint inversion of Z and T, and nRMS < 2 for separated inversion of these transfer functions. The preferred resistivity model reveals remarkable large-scale deep conductive structures in the area. The electrical signature of the major suture zone - Transbrazilian lineament (TBL) - is not uniform from north to south, and sometimes is not well demarcated, as also observed in previous MT works. The new model suggests a lithosphere-asthenosphere boundary ~150 km in agreement with other studies, however intriguing prominent and wider deep conductor shallowing in the central part of the model where high heat flux is also observed suggests a mantle-crust control of this lineament and the shape of the block. Parnaíba block has a lateral discontinuity in all E-W profiles, going from North to South, that match the proposed limits between domains Grajaú and Teresina domains, the latter showing thinning in the N profiles and dipping E-W in S profiles.

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3-D Inversion of magnetotelluric data over the Southern Indian Shield Region

DOI: 10.57757/IUGG23-3329 - LINK

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[3]Absolute Imaging International India Ltd., Seismic Processing, Noida, India

The southern Indian shield region (SISR) is dominated by several tectonic blocks separated by a complex set of faults and shear zones. The resistivity structure of the lithosphere beneath the SISR is investigated by using 65 magnetotelluric stations. The NW-SE trending, 800 km long profile with an inter-site spacing of about 25 km covers a part of the Deccan volcanic province (DVP), western Dharwar craton (WDC), and southern granulite terrain (SGT). The raw data consists of broadband time-series records within the period range of 0.01 to about 3,000s. Firstly, 2-D modeling was carried out to get the geo-electrical map of the sub-surface. SISR is a geologically complex unit, and in this type of region, sometimes 2-D modeling does not give significant details of off-profile prominent features. So, 3-D MT inversion was carried out with the diagonal (Zxx, Zyy) and off-diagonal (Zxy, Zyx) elements. Conductive features obtained in 2-D models are spatially correlated with features in the 3-D model. The features mapped in the 3-D resistivity model can be interpreted in terms of the deep seated faults, rifts, and shear zones. This study observes the southward subduction polarity between the western Dharwar craton and southern granulite terrain. The lithospheric thickness increases from DVP to SGT. The present study results are well correlated with the geological features mapped in the area.

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JS03b - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

ECS Awardee 2023: Electrical rock physics for underground CO2 storage

DOI: 10.57757/IUGG23-1720 - LINK

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[2]Technical University Bergakademie Freiberg,
Institute of thermal- environmental and natural products process engineering, Freiberg, Germany
[3]Institut de Physique du Globe de Paris, Physics of Natural Sites, Paris, France
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[5]Jacobs University Bremen, Department of Physics Earth Sciences, Bremen, Germany

The electrical properties of rocks are sensitive indicators for CO2 migration processes. Due to their sensitivity to the pore fluids, electric and electromagnetic geophysical methods bear a great potential for monitoring underground CO2 storage reservoirs and for early-warning leakage detection. However, CO2 is a reactive gas which massively interacts with other pore fluids as well as the solid rock matrix. Therefore, classic petrophysical relationships do not necessarily apply.

With laboratory studies we investigate the impact of CO2 on the complex electrical conductivity of water-bearing rocks with and without a reactive mineral matrix under geologically relevant pressure and temperature conditions. By combining the rock physics findings with site-specific 3D time-lapse simulation studies, we can develop optimized electromagnetic monitoring setups with respect to coverage and resolution.

The presented results provide insight into the reactive processes in rocks subject to CO2 and can be used to correct for chemical interactions during the interpretation of electrical measurements in terms of saturation. Our experimental and numerical results have implications for leakage detection methods and monitoring the evolution of mineral dissolution and/or precipitation processes at the grain-water interface during underground CO2 storage. Additionally, the results also advance our understanding of geogenic CO2-rich geosystems, such as volcanic terrains with gas emissions or low-temperature CO2 discharges.

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JS03b - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The electrical conductivity structure beneath the Koillismaa-Näränkävaara complex in northern Finland

DOI: 10.57757/IUGG23-1875 - LINK

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The Koillismaa-Näränkävaara complex in North-eastern Finland is currently studied with a variety of geophysical and geochemical investigations to better understand its geological history and assess its mineral potential. The area is characterized by an East-West oriented deeply seated ultramafic intrusion within the granitoid bedrock which has been indicated by gravity and magnetic anomalies as well as 2D inversion of sparse magnetotelluric (MT) data. It was successfully drilled at a depth of 1.5 km by the Koillismaa Deep Hole. The aim of this study is to better delineate the geological structure around the Koillismaa Deep Hole area. We collected 70 MT sites along an approximately 40 km long profile across the intrusion. In addition, we also tested our newly acquired EM transmitter and collected a densely sampled controlled source AMT (CSAMT) profile across the Koillismaa Deep Hole at the centre of the MT profile.

Data analysis of the MT data shows prominent geoelectrical strike direction perpendicular to the intrusion. However, it also shows a change of strike direction with depth by 20°. We will discuss possible causes of observed anisotropy and show inversion results of the MT data and compare it with latest results from our CSAMT survey. Our EM results will be further compared to other existing geophysical data such as borehole logs, gravity, and magnetic modelling as well as petrophysical measurements of the drill core.

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Lateral variations in the water content and mantle-crustal controls on mineral systems revealed by 3-D electrical conductivity imaging

DOI: 10.57757/IUGG23-1914 - LINK

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Electrical conductivity variations provide unique constraints on chemistry, mineralogy, and physical structure of the crust and mantle. As a physical property, conductivity is highly sensitive to the presence of fluids and volatiles (i.e., hydrogen). Here, we present a new 3-D electrical conductivity model (MECMUS) derived by inverting data from more than 1300 USArray MT stations covering 90% of the contiguous United States on a quasi-regular 70-km grid. The use of a novel multi-scale imaging approach and locally refined meshes allows us to consistently incorporate a large range of spatial scales and image 3-D electrical conductivity distribution from the surface down to mantle transition zone. We find conductivity variations that correlate with known continental structures such as due to the active tectonic processes within the western United States as well as the presence of deep roots beneath cratons. We further interpret conductivity variations in terms of the upper mantle water content by coupling electrical conductivity with constrains on mantle thermo-chemical structure derived from the analysis of seismic data (in the form of P-to-s and S-to-p receiver functions). Further, we explore the links between electrical conductors and lithospheric controls on occurrence of critical mineral deposits.

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Joint interpretation of more than 600 Magnetotelluric sites and five 2-D Seismic lines and well-log to explore an oil field

DOI: 10.57757/IUGG23-1080 - LINK

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A high resolution magnetotelluric investigation was conducted in the Sehqanat oil field, SW of Iran, in 2020 (Phase II) to map geoelectrical structure of the region from surface down to several kilometers. The Sehqanat oil field is located in sedimentary Zagros zone comprising ranges of the biggest oil fields in Iran. The most interesting target in this survey was geological contact between Gachsaran (Cap Rock) and Asmari (Reservoir) formation. According to the electrical logs information, large resistivity contrast exists at the boundary of two mentioned formations. The Gachsaran formation is formed by tens to hundreds meter of evaporites which is highly conductive (ca. 1-10 ohm-m) and the Asmari formation, in contrary, comprising of dense carbonates with more electrical resistivity range (more than 100 ohm-m). The broadband magnetotelluric data were collected in a 3-D pattern at more than 600 stations along five parallel southwest-northeast profiles crossing the main geological trend of the study area. Velocity information extracted from seismic data acquired in the region used to make initial model for magnetotelluric modeling. In order to image a comprehensive subsurface resistivity map throughout the Sehqanat oil field, three-dimensional inversion was performed on the magnetotelluric data as well as two-dimensional routine. The 2-D inversion results depicted the main resistivity structures while the 3-D inverted model shows significantly more details and consistency.

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JS03c - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The Zagros Collisional Zone: An example of the interplay between shallow and deep structures

DOI: 10.57757/IUGG23-1866 - LINK

Magdala Tesauro[1], Petra Maierova[2], Alexander Koptev[3], Alberto Pastorutti[1], Tommaso Pivetta[1], Ivan Koulakov[4], Carla Braitenberg[1]
[1]University of Trieste, Mathematics and Geosciences, Trieste, Italy
[2]Czech Geological Survey, Czech Geological Survey, Praha, Czech Republic
[3]GFZ German Research Centre for Geosciences- Potsdam- Germany, 2.5 Geodynamic Modeling, Potsdam, Germany
[4]Trofimuk Institute of Petroleum Geology and Geophysics, Prospekt Akademika Koptyuga, Novosibirsk, Russian Federation

Subduction of the Neotethys Ocean resulted in collisions of continental plates, with formation of Cenozoic orogens. The different shapes and structures of various segments of these young orogens, such the Zagros Collisional Zone, suppose a complex interplay of shallow and deep structures, producing different degrees and styles of deformation. As part of the PRIN 2017 project, we analyze several types of recently acquired data (e.g., seismic tomography models of the crust and upper mantle, Moho depth, seismicity distribution, and surface topography). We find that the NW and central Zagros is characterized by a zone of thickened crust of variable width and overlain by topography that exhibits large height variations over small distances, in the central part of the collisional zone. These variations are accompanied by sharp lateral changes in the number of seismic events and velocities/temperatures at depths of ~100 km.

We attribute these observations to relamination processes (i.e., the detachment of Arabian crust from the subducting lithospheric mantle and its underthrusting beneath the crust of the overriding plate), which are controlled by the variable geometry and stiffness of the overriding and subducting plates. This hypothesis is tested by performing a series of numerical experiments, using the numerical code I2VIS [1], that simulates relamination processes, occurring during continental collision. The consistency of the results is also verified through forward models of the static gravity field of the modelled structures, which are compared with the present-day observed gravity.

References

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JS03c - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Crustal structure of the east himalayan syntaxis and its relation to the rapid uplift and exhumation

DOI: 10.57757/IUGG23-3806 - LINK

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School of Geophysics and Information Technology, Beijing, China

The East Himalayan Syntaxis (EHS) is featured with an abrupt U-turn of all geological boundaries, geomorphic features and river systems at the east end of the Himalayan orogenic belt. The EHS is believed to be the region with strongest Cenozoic uplift and exhumation in Tibetan Plateau. The most significant geomorphology feature in EHS is the over 7000m Gyara Peri (GP) and Namcha Barwa (NB) peaks, which rise abruptly from the <3000m surrounding Yarlung-Tsangpo canyon. Since the late Pliocene, the central Namcha Barwa area has experienced fast uplift and has developed a series of high-angle fault networks that are focused around EHS. Magnetotelluric array measurements were used to map the 3D electrical structure beneath the EHS in order to better understand the reasons beneath the rapid growth of regional elevation. The inversion model reveals crustal high conductivity anomalies around the NB region, which may be related to the decompression melts caused by the rapid uplift of the region. On the other hand, the crustal structure directly beneath NB is imaged as highly resistive NNE directed anomaly. This feature is consistent with previous regional resistivity model and the velocity structure discovered by magnetotelluric and surface wave results. The resistive "wedge" may reflect the northward intrusion of deep materials into the crust of the Lhasa block, which further induces the uplift of regional structure. With the gradual intrusion of the wedge, the uplift may gradually expands to the northeast, forming the long and narrow surface compound anticline responses.

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The time-dependent thermal trigger for intracontinental rifting and break-up of continents

DOI: 10.57757/IUGG23-3811 - LINK

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Ocean closure and collisional orogeny frequently enrich the lithospheric mantle in radioactive elements (uranium, thorium, potassium) due to the subduction of continent-derived sediments and continental crust. According to thermal modeling, increased content of radioactive elements within the anomalous lithospheric mantle causes a time-dependent rise of temperature, providing favorable conditions for intracontinental rifting more than 50-100 million years after the closure of the ocean. In addition, the obtained results indicate that in a global-scale mantle convection system, there is a clear tendency for the mantle upwellings to move towards the thermally anomalous upper-mantle block over time. Concentrating convectional upwellings under the anomalously hot lithosphere can cause extensional stresses that can theoretically trigger the break-up of the already thermally weakened, continental lithosphere. Moreover, our results provide an explanation of why rifting and continental break-up occur along or in close vicinity to the suture zones not immediately after the orogenic event but with a delay in time, dependent on the concentration of heat-producing elements in the anomalous mantle block and the size of this block. Thus, the presence of structural/compositional inhomogeneities within the anomalous lithosphere plays a rather secondary role, affecting mostly the geometrical configuration of the rifts. Therefore, a newly discovered, time-dependent process of weakening the continental lithosphere can be responsible for intracontinental rifting and the subsequent continental break-up and is controlled by the enhanced content of radioactive elements within the anomalous lithospheric mantle of the suture zones.

Ocean closure and collisional orogeny frequently enrich the lithospheric mantle in radioactive elements (uranium, thorium, potassium) due to the subduction of continent-derived sediments and continental crust. According to thermal modeling, increased content of radioactive elements within the anomalous lithospheric mantle causes a time-dependent rise of temperature, providing favorable conditions for intracontinental rifting more than 50-100 million years after the closure of the ocean. In addition, the obtained results indicate that in a global-scale mantle convection system, there is a clear tendency for the mantle upwellings to move towards the thermally anomalous upper-mantle block over time. Concentrating convectional upwellings under the anomalously hot lithosphere can cause extensional stresses that can theoretically trigger the break-up of the already thermally weakened, continental lithosphere. Moreover, our results provide an explanation of why rifting and continental break-up occur along or in close vicinity to the suture zones not immediately after the orogenic event but with a delay in time, dependent on the concentration of heat-producing elements in the anomalous mantle block and the size of this block. Thus, the presence of structural/compositional inhomogeneities within the anomalous lithosphere plays a rather secondary role, affecting mostly the geometrical configuration of the rifts. Therefore, a newly discovered, time-dependent process of weakening the continental lithosphere can be responsible for intracontinental rifting and the subsequent

continental break-up and is controlled by the enhanced content of radioactive elements within the anomalous lithospheric mantle of the suture zones.

JS03c - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

3D palinspastic reconstruction of the Anemzi syncline (Central High Atlas) as a result of a paleomagnetic and structural study

DOI: 10.57757/IUGG23-1803 - LINK

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Our study area is located in the Central High Atlas (Morocco), which is the largest intraplate mountain chain in North Africa. It consists of a series of basins developed during the Triassic and Jurassic subsequently inverted during the Cenozoic as consequence of the convergence between African and European plates. The area features NE-SW and ENE-WSW trending folds that interfere with smaller-scale oblique and perpendicular folds. Previous studies have shown that Jurassic rocks of the Central High Atlas are affected by a regional interfolding remagnetization that separates two different tectonic events: the Jurassic extension and the Cenozoic inversion. Remagnetization has been dated as Cretaceous (ca. 100 Ma) and is related with burial.

A high resolution paleomagnetic study (91 sites in about 35 km^2) was carried out on the Anemzi syncline, a paradigmatic structure of the Central High Atlas. By means of Small Circle methods, both the remagnetization direction and the paleobedding (i.e. the bedding attitude at the remagnetization time) were calculated and used restore the 3D structure at 100 Ma times, which represent the structure developed during the extensional stage. Restoration is compared with the present-day structure to better understand the evolution of the Central High Atlas during both the basinal stage and the subsequent inversion and to extract relevant clues about the importance of the inheritance of extensional structures (normal faults, gabbro intrusion, diapirism, etc.) during mountain building.

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JS03c - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The role of the Iceland plume in the NE Atlantic continental breakup derived from a data-integrative 3D model

DOI: 10.57757/IUGG23-2778 - LINK

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The present-day state of the NE Atlantic lithosphere is the product of a complex geodynamic history that includes the continental breakup between Greenland and Eurasia about 55 million years ago, after multiple phases of extensional deformation and the emplacement of the Iceland plume. Open questions related to the process of continental breakup in this area are which role the Iceland plume played and whether we can image the traces of it in the present-day configuration of the crust and mantle. With the present work we aim to contribute to these questions by means of the integration of available geoscientific observations - including seismic profiles, existing geological maps and models, seismic mantle tomography and, particularly, gravity data - into one consistent three-dimensional model. The final model resolves the main structural characteristics, as well as the density distribution, of the crust and upper mantle of the entire NE Atlantic including its conjugate margins of Greenland and Norway. It allows us to correlate the obtained density anomalies in the crust with proposed surface indicators of the plate's journey over the plume. Besides, mantle density anomalies can be related with the present-day plume location and its interaction with the mid-ocean ridges. The model also indicates major differences in the density configuration between both conjugated margins increasing with the distance to the plume and towards the sheared margin segment. Altogether, our results indicate that the breakup of the continent, with its pre-existing crustal configuration, could have been facilitated by the presence of the plume.

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JS03d - Probing the Earth’s Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Uncovering the Secrets of Earth’s Interior : a study of continental hotspots tracks using GOCE gravity gradients

DOI: 10.57757/IUGG23-4245 - [LINK]

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This study aims to find evidence of a residual thermal anomaly along the path of a hotspot beneath the continental lithosphere using gradiometry data.
Considering a simple model of thermal anomaly, we calculated the associated gravity gradients and found that the horizontal component which is highly sensitive to the directional structure of the source has a magnitude of several hundred mEötvös, well above the current detection level of the data.Using GOCE satellite data, we created scale-orientation diagrams in four regions (Africa, Greenland, Australia, and Europe) to determine the direction and spatial scale of the strongest signal. We searched for a signal in the direction of plate movement, with a spatial scale of a few hundred kilometers (scale of the plumes). We then determined the ancient positions of the hotspots over the lithosphere and created maps of Bouguer gravity gradients and topographic gradients, filtered at a spatial scale of a few hundred kilometers and oriented in the direction of the hotspot's path. Interpreting these signals is challenging as it is difficult to separate the residual thermal anomaly from the surface topography and related crustal root , if the topography is aligned with the direction of plate motion and/or correlated with the volcanic chains generated by the plume.
Despite these challenges, the results shows that gradiometry data has the potential to track hotspots in the continental lithosphere for tens of millions years.

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JS03d - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Connecting subduction and collisional processes in East Antarctica during Gondwana assembly with airborne and satellite geophysical imaging

DOI: 10.57757/IUGG23-2656 - LINK

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[7]*Technical University of Denmark, Department of Space Research and Technology, Lyngby, Denmark*
[8]*British Antarctic Survey, Palaeo Environments- Ice Sheets and Climate Change, Cambridge, United Kingdom*
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East Antarctica is the least understood continent involved in the assembly of Gondwana, a key stage in the global supercontinent cycle. Thick crust stretches from Dronning Maud Land to the Gamburtsev Subglacial Mountains, suggesting that the Kuunga Orogen, formed during the collision of India and East Antarctica during Gondwana assembly, had a significant impact on the Precambrian lithosphere of parts of interior East Antarctica. Geological and geophysical research has revealed key aspects of the collisional East African-Antarctic Orogen and the subduction-related Ross Orogen along the paleo-Pacific margin of Gondwana. However, the paths and architecture of these different orogens in the entirely ice sheet covered and remote interior of East Antarctica have remained more difficult to investigate, making it even more challenging to link subduction and collisional processes leading to Gondwana assembly and growth.

Here we present a new satellite-conformed aeromagnetic anomaly compilation that includes data recently collected between the interior of Dronning Maud Land and South Pole, together with airborne and satellite gravity imaging and seismological and geological constraints that provide tantalising new views into different crustal provinces, cratons and orogens in interior East Antarctica. We propose that a suture zone, partially exposed in the Shackleton Range, may cross the continent linking major fault systems imaged in the Gamburtsev Province and Princess Elisabeth Land. By superimposing our geophysical layers on a new plate tectonic reconstruction, we explore the potential evolution of accretionary and collisional stages in East Antarctica during the assembly of Gondwana from Edicaran to Cambrian times.

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JS03d - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Optimising the understanding of the East Antarctic lithosphere through the 'GRIT' geophysical instrument facility, computational approaches and current/future field campaigns

DOI: 10.57757/IUGG23-1149 - LINK

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The lithosphere of East Antarctica, undoubtedly as complex as its neighbours in Gondwana, presents particular challenges in progressing the understanding of its tectonic nature due to its remote location and the harsh environment for on-ground geophysical instruments. Satellite-based and airborne data gathering has enabled composite maps for subglacial topography and potential field properties to be developed (e.g., Bedmap3, ADMAP2, ADGRAV) while international initiatives (such as 3D-Earth) provide 3D reference models of the crust and upper mantle with improving on-ground constraints for properties such as seismic wavespeed.

In this contribution, we share information on a new facility 'Geophysical Research Instrumentation for AnTarctica' (GRIT) that is enabling new ground-based data to be collected across multiple geophysical techniques (currently seismic, magnetotelluric, GNSS). We present an updated seismic crustal structure for the East Antarctic sector between Mawson and Dumont D'Urvillle stations (including new locations on remote outcrops), in the context of recent satellite-based studies. We also illustrate the relative importance of different observables as 'integrator' datasets for multivariate studies that show exceptional promise in multidisciplinary geoscience research, and how computational approaches can provide quantitative metrics to optimise targets for future field campaigns.

A better understanding of the heterogeneous lithosphere and deeper Earth, and interactions between the solid Earth and ice sheets, is urgently needed for Antarctica as this informs the response of ice sheets to global change. Combining the results of computational approaches and international initiatives for data collection and collation will result in optimised and accelerated research progress in the coming years.

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JS03d - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Precambrian lithospheric structure in East Antarctica controls Phanerozoic basin forming and Gondwana breakup geometry

DOI: 10.57757/IUGG23-2273 - LINK

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East Antarctica is the keystone to Gondwana and is fundamental to the understanding of continental breakup and the distribution of continents since the Jurassic, with further implications for the formation of today's oceans and ice sheets and evolution of climate. Analysis of multiple geophysical datasets in East Antarctica, including radio-echo sounding, potential fields and seismic datasets have revealed the distribution of sedimentary basins within East Antarctica. Differences in the morphology and orientation of sedimentary basins define lithospheric domains separated by basement-dominated regions. The basement highs are defined by multiscale linear features evident in gravity, bed topography and seismic tomography models. These boundaries, we suggest, indicate the margins of former continental blocks that were assembled in the Precambrian to form East Antarctica. Rheological contrasts at block margins controlled later deformation during Phanerozoic extension. First, the formation of variably-oriented sedimentary basins in the Devonian to Triassic is consistent with reactivation of prior architecture and the distribution of major basin-dominated regions is indicative of differences in lithospheric rheology and composition - warmer and compositionally more fertile lithosphere is prone to subsidence. Second, the basement highs are aligned with key features of Gondwana breakup in the Jurassic to Eocene including the Africa-Madagascar-Sri Lanka triple junction, the Kerguelen Plateau, the George V fracture zone of Australian-Antarctic basin and the Macquarie Ridge. We suggest that the differential lithospheric structure of East Antarctica including mantle, crust and basins led to the localisation of these features and fundamentally controlled the geometry of Gondwana breakup.

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JS03d - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Constraining lithosphere viscosity structure using Lower Mississippi River long profile deformation

DOI: 10.57757/IUGG23-3446 - LINK

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In this investigation we model solid Earth deformation as constrained by vertical displacement of the Lower Mississippi River long profile over the past ~80 kyr. These observations are compared to output from a model that simulates glacial isostatic adjustment and sedimentary isostatic adjustment using a spherically-symmetric, viscoelastic Earth model. Observations of long-profile displacement based on optically-dated sediment cores, were revised to account for the effect of fault displacement in the southern end of the long profile inferred in some recent studies. Due to the relatively localized sediment loading associated with the Mississippi Delta System, the vertical displacement of the long profile over the past ~80 kyr is highly sensitive to lithospheric structure. For this reason, these observations offer a valuable opportunity to constrain mechanical properties of the lithosphere beneath the south-central United States. To pursue this opportunity, we consider multiple model scenarios in which the lithosphere is either entirely elastic (a common assumption in surface loading studies) or has internal viscosity structure. In the latter case, viscosity structures are determined using a range of plausible geothermal gradients and seismic constraints on Moho depth. In the elastic case, model lithosphere thicknesses are fixed at 46 km, 71 km, 96 km, or 120 km. For each modelling scenario (elastic vs viscous), constraints on lithosphere thickness and structure, and the ability of the model to match the observations will be presented.

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JS03d - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

A Robust Approach for high-resolution GNSS-based Surface Deformation Imaging

DOI: 10.57757/IUGG23-2792 - LINK

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The proliferation of Global Navigation Satellite System (GNSS) stations, and their derived 3D velocities, has offered both opportunities and challenges to image the surface deformation field. We merged and improved two existing robust imaging techniques: MELD (Kreemer et al. 2018, 2020) for horizontal strain rate and RNI (Kreemer et al., 2020) for vertical land motion. Both approaches aim at a robust high-resolution estimation with realistic uncertainties and without none to little a priori constraints. Our new algorithm (R3DI: Robust 3D Imaging) integrates both approaches and aligns the station selection.

MELD and R3DI rely on a multivariate median estimation of strain rate and plate rotation calculated from a set of stations and corresponding triangles. While MELD was developed specifically for imaging strain rates in low-straining areas, R3DI is designed more generally and based on an iteratively increasing number of stations until the results are significantly above a given SNR value. This approach allows a robust estimation, while the achieved spatial resolution depends solely on the station network's density and the local strain rate. The implemented concept was validated using synthetic data using a checkerboard test performed with real station locations in Europe and simulated 100x100km extension and compression cells.

After discussing the overall approach and the validation results, we will present horizontal and vertical deformation patterns derived from European and North American dense station networks. Finally, we will compare the results to the prior estimates for Europe from Kreemer et al. (2020) and North America from Kreemer et al. (2018).

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Lithospheric evolution of eastern Arabia based on surface wave and receiver function analyses

DOI: 10.57757/IUGG23-1988 - [LINK]

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The tectonic evolution of Eastern Arabia comprises three major events that must have modified the entire lithosphere below the present-day passive continental margins. Pan-African plate assembly during the Late Proterozoic established NNE-striking structural trends. Permo-Triassic Pangean breakup and rifting created two rift axes to form the present-day plate geometry. SW-directed obduction of the Semail Ophiolite during the Cretaceous shaped the present-day geology of northern Oman. Recent anisotropic ambient noise tomography, surface wave analysis of earthquake data and receiver function analysis reveal the present-day lithospheric thickness of ∼100 km and the highly variable internal structure of the East Arabian continental crust.

A NNE-striking contrast in the lower crust separates felsic from intermediate lithologies in northern Oman and is interpreted as being established during Pan-African orogeny. High V_S in the lower crust of northeastern Oman likely relate to Permian mafic intrusions emplaced during Pangean breakup. Mild crustal thickening below the topography is attributed to Late Cretaceous times, where continental subduction led to underthrusting and thickening of the crust and ultimately ophiolite obduction. Since present-day topography emerged only ~30 Ma after obduction ended, we argue that lithospheric thickness, margin perpendicular anisotropy and contemporaneous basanite intrusions are indicative of a relaxed state of stress at that time. Therefore, we propose that marginal erosion of the base lithosphere during Late Eocene facilitated margin-wide emergence of the Oman Mountains. Altogether, the lithospheric configuration in northeastern Arabia preserves imprints from Late Proterozoic Pan-African assemblage, Permian Pangean break-up, Late Cretaceous subduction and obduction, and Cenozoic post-obduction evolution.

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JS03e - Probing the Earth’s Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Distinct lithospheric structure and deformation in the Xing'an-Mongolian Orogenic Belt

DOI: 10.57757/IUGG23-0377 - LINK

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The Xing'an-Mongolian Orogenic Belt (XMOB) is a key area to study the tectonic evolution of northeast Asia, as it has retained the records for the processes of both the closure of the Paleo-Asian Ocean and the Mongol-Okhotsk Ocean and the subduction of the (Paleo-)Pacific plate. We constrained the lithospheric structure across the XMOB by receiver function imaging and shear wave splitting analysis from a dense seismic array. The lithosphere–asthenosphere boundary (LAB) is coherently imaged in different tectonic blocks. The mid-lithospheric discontinuity is also identified at ~75-100 km depth over the deeper LAB (~110-130 km) beneath the western side of the North-South Gravity Lineament (NSGL), roughly at the same depth as the LAB beneath the eastern side of the NSGL. Distinct patterns in seismic anisotropy were identified which are roughly separated by the NSGL. The large variations in lithospheric thickness, seismic anisotropy and crustal structure between the two sides of the NSGL indicate that it might likely caused by different tectonic processes in the two sides, indicating that the NSGL might represent the western boundary influenced by the subduction of the (Paleo-)Pacific Plate. The eastern side of the NSGL is characterized by a thinned lithosphere of less than 100 km and dominant NW-SE fast shear wave polarization direction, which reflects considerable lithospheric deformation probably related to the Mesozoic-Cenozoic subduction of the (Paleo-)Pacific plate. An integration of our results and geological observations suggests that the area in the west of the NSGL may not have been affected by the (Paleo-)Pacific subduction.

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JS03e - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Segmentation of the Indian lithosphere along the Himalayan arc: A multi-proxy approach

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Segmentation of the Indian lithosphere along the seismically active Himalayan collision belt, suggested by seismological and GPS studies, and analysis of topography and Bouguer gravity anomaly data, is one of the significant parameters to assess the maximum rupture area and hence the seismic energy release potential. These studies, confined to the Himalaya-Tibet region, linked major segmentation boundaries to pre-existing tectonic fabric of the Indian plate. We have studied this problem from the perspective of lithospheric flexural properties in the Himalaya-Ganga foreland basin system for possible segmentation. For this purpose, we have used the relationship between the foreland basin width (WFB) and the segment length between the Main Frontal Thrust and the Man Central Thrust (δFC) as a proxy to test possible correlation between these two parameters along the arc. The results suggest a major segmentation boundary along the Indo-Nepal border in addition to other previously discussed segmentations coinciding with major transverse ridges in the Ganga Basin. This segmentation boundary coincides with the Great Boundary Fault separating the Aravalli-Delhi mobile belt (ADMB) from the Vindhyan Basin further south. Further, we have analyzed a geomorphic index, normalized channel steepness (ksn), along the arc using the ALOS elevation dataset to test whether there is any relation between the ksn and the segmentation boundaries. Our results bring out spatial variability in the ksn along the arc and support the above segmentation. We infer a role of this segmentation boundary in limiting westward propagation of the rupture front of the 1505 paleo-seismic event.

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JS03e - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Seismic imaging of the crust beneath the Aravalli Delhi Fold Belt in Northwestern India

DOI: 10.57757/IUGG23-2729 - LINK

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The crust beneath a 250km long NW-SE trending profile across the Proterozoic Aravalli Delhi Fold Belt in northwestern India was imaged through P receiver functions(RF). We used teleseismic data recorded by 25 closely spaced(10-15km) broadband seismographs deployed on the profile passing through the Marwar craton(MC), Delhi fold belt(DFB), banded gneissic complex(BGC) and Vindhyan basin(VB). About 1600 RFs were generated using the iterative time domain deconvolution technique. The H-k grid search reveals the crustal thickness(H) and Vp/Vs(k) to be ranging from 35km to 53km and 1.70 to 1.90 respectively. Common conversion point image reveals lateral variations in the continuity of the Moho and the intra-crustal discontinuities. Crustal thickening upto 53km is observed beneath DFB while a flat Moho is imaged at ≈40km beneath the rest of the profile. A steep, SE dipping moho was imaged beneath DFB that may represent the subduction of the Marwar craton beneath the Aravalli craton in the east. A crustal scale feature dipping NW and extending from moho to the near surface beneath BGC was distinctively imaged that corresponds to the Jahazpur thrust. Low Vp/Vs(≈1.73) reveal a felsic crust beneath BGC while DFB and VB are characterized by high Vp/Vs(≈1.82) indicating an intermediate to mafic crustal composition. Neighbourhood algorithm inversion reveals ≈10km thick, high velocity layer(Vs≈4km/s) at the base of the crust suggesting significant magmatic underplating. Our results correlate very well with those of the deep seismic reflection studies along the same profile and provide additional information on the continuity of the crustal structure and composition.

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JS03e - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The next cascadia slab model

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Detailed knowledge about the location and properties of the structures that host the megathrust is required to predict ground motions, model tsunami hazards and better understand subduction zone processes in Cascadia. Here we present our efforts to bring forward a new, detailed slab model based on azimuthally variable receiver functions from almost 300 on-shore 3-component broadband seismic stations.

We observe a characteristic succession of a negative top-, a positive central- and the positive oceanic Moho-conversion, where either the top or central conversion may be absent. We interpret it as the subducting oceanic crust that is at places overlain by, or contained within, a low-velocity zone. Inverse modeling of synthetic receiver functions allows us to resolve the strike and dip of this structure, the interface depths and seismic velocities of the intervening material along the fore-arc.

The top conversion exhibits a progressive landward evolution displaying (i) a weak contrast with overriding crust near the coast, (ii) full expression with the development of an upper low-velocity zone downdip, and (iii) disappearance in advance into the fore-arc, where the oceanic crust is inferred to turn to eclogite.

The thickness of the entire structure frequently exceeds the thickness of the oceanic crust offshore. At depth, the location of the central converter approximately correlates with the location of low-frequency earthquakes. These observations suggest that the subduction megathrust either continues downdip, a few kilometers below the top conversion, or widens into a distributed shear zone that includes upper plate material.

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JS03f - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The effects of hydrothermal circulation in subduction zone understanding from decreasing magnetization of subducting oceanic crust and numerical geodynamic approach

DOI: 10.57757/IUGG23-1101 - [LINK]

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Estimating temperature in subduction zones is not easy because the tectonic structures in the area are complicated and it is not possible to reach and directly measure the temperature of subducting slab. In addition, existing water flows in the highly permeable sediment layer interfere with temperature measurements on the seafloor. The observed systematic decays of the seafloor spreading magnetic anomalies in subduction zone give insight into using it as a non-contact geothermometer. We interpret this first decay in the magnetic anomaly amplitude as reflecting the opening of normal faults and fissures from the outer flexural rise, and the renewed circulation of seawater into the oceanic crust, resulting in additional alteration of the magnetic mineral. And the systematic decays are happened in subducted oceanic crust following two steps: (1) the thermal demagnetization of the extrusive basalt layer where titanomagnetite and titanomaghemite reach their blocking temperature between 150-350°C; and (2) the magnetization of the deeper crustal layers slowly decreases, reflecting the progressive heating of the slab toward the Curie temperature of magnetite, 580 °C. These results indicate that the temperature of the subduction zone might be higher than the previous understandings. To identify it, we developed a numerical geodynamic model for subduction zones. Of course, the thermal structure in the subduction zone can be explained in large part by the heat conduction as in the existing geodynamic studies. However, our result support that hydrothermal circulations have a significant affect that changes in the physical properties and thermal structures of subduction zones.

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JS03f - Probing the Earth’s Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

3-D thermal structure and dehydration in the southern Chile subduction zone and relation to interplate earthquakes and the volcanic chain

DOI: 10.57757/IUGG23-0774 - LINK

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Department of Geophysics Faculty of Physical and Mathematical Sciences, Santiago, Chile

In the southern Chile subduction zone, the Nazca plate is subducting beneath the South American plate. This region was recently struck by great megathrust earthquakes and is characterized by the existence of a volcanic chain. In this study, we calculated the three-dimensional thermal structure in the southern Chile subduction zone associated with the subduction of the Nazca plate by using numerical simulations. Based on the obtained temperature distribution, we determined the temperature ranges for the coseismic slips of the two megathrust earthquakes and temperatures at the hypocentres of the interplate earthquakes. In addition, the distributions of the water content and dehydration gradient were calculated by using the phase diagrams and were compared with the location of the volcanic chain. As a result, we found that coseismic slips occurred only at temperatures lower than the 350 °C isotherm. This finding occurs because the effective friction coefficient increases as the slip velocity increases at the plate boundary where the temperature is higher than 350 °C. In addition, the hydrous minerals in and above the slab release fluids through dehydration reactions, which decrease the melting point of the mantle wedge, contributing to the formation of the volcanic chain.

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JS03f - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Using aeromagnetic, geologic and tectonic data to establishing relationship between hydrothermalism and fracturation: Case of Ain Ouarka western Algeria

DOI: 10.57757/IUGG23-3909 - LINK

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The present work is based on a correlation with surface geothermal manifestations, aeomagnetism, and tectonic fracturing of Ain Ouarka zone, which is located in the Western Saharan Atlas of Algeria.

Using multi-source data, 114 fracture faults are identified and analyzed especially in the Mesozoic formations.

Our results show that fractures are distributed along three main directions NNW/SSE and WNW/ESE and an atlasic direction oriented N70°. For the faults depth, we relied on the processing of aeromagnetic data. Our results show that the depths of the tectonic structures argue in favor of a collapsed zone along the W-E fault of Ain Ouarka where the depths increase from 0.5 km to more than 2 km approaching the central zone. It is in this zone of cataclysm that the emergence of sources of hot water are noted. The results obtained after the processing of the magnetic data show that the distribution of the depths of the basement on the two banks of the W-E fault reaches almost 100 m thus showing the vertical throw of the W-E fault. The hydrodynamic model elaborate, show that under a regional tectonic regime probably recent, a collapsed zone has been highlighted. This cataclysm engendered uplift of plutonic reservoir at shallow depth. Rainwater infiltrates through permeable Mesozoic formations, flows towards the cataclysm zone. Subjected to high temperatures of plutonism, these waters warm up and rise under the effect of the low density to reach the surface in the form of hydrothermal springs.

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JS03f - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Deduction of Heat flow from aeromagnetic anomalies of Gongola sub-basin, northern Benue trough, Nigeria

DOI: 10.57757/IUGG23-2133 - LINK

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Heat flow investigation of the Gongola sub-basin in northeastern Nigeria has been done from a 2D spectral analysis of recently acquired high-resolution aeromagnetic data as a means to elucidate likely concealed geothermal reservoirs in the basin. The aeromagnetic data, bounded by latitudes 9.0^{o}N and 12.0^{o}N and longitudes 10.0^{o}E and 12.5^{o}E, were divided into 20 overlapping blocks of 180 x 180 km and each block analyzed to estimate the Curie-point depths and ensuing geothermal gradients and heat flow isotherms. The results revealed Curie-point depths ranging from 20.03 to 29.83 km, geothermal gradients ranging from 19.44 to 28.69 ^{o}C/Km, and the ensuing heat flow varying between 48.61 and 72.39 mW/m^2. The results demonstrate that the study area is dominated by a thick crustal layer (above 15 km) and heat flow that is less than both the global average of 87 mW/m^2 and the accepted value of 80 - 100 mW/m^2 for anomalous geothermal conditions. Therefore, this study deduces that the area may not have traces of anomalous geothermal settings, having shown no zone of considerable crustal attenuation and elevated heat flow. Even so, the study contributes to the understanding of the thermal state of the lithosphere and regional heat flow variations of the geological formation of the Gongola sub-basin.

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Latest version of the World Digital Magnetic Anomaly Map (WDMAM v.2.1) released

DOI: 10.57757/IUGG23-2797 - [LINK]

Jerome Dyment[1], Yujin Choi[1], Vincent Lesur[2], Andreina Garcia-Reyes[1], Manuel Catalan[3], Takemi Ishihara[4], Tamara Litvinova[5], Mohamed Hamoudi[6]
[1]Université Paris Cité- IPGP and CNRS, Marine Geosciences, Paris, France
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[3]Real Instituto y Observatorio del Armada, Geophysics, Cadiz, Spain
[4]AIST, Geological Survey of Japan, Tsukuba, Japan
[5]VSEGEI, Geophysics, St. Petersburg, Russian Federation
[6]Université des Sciences et Technologies Houari Boumediene, Geophysics, Algiers, Algeria

The last version of the World Digital Magnetic Anomaly Map (WDMAM v. 2.0) was released in 2015 (Dyment et al., EPSL, 2015; Lesur et al., EPS, 2016) with the mandate to update it using the same methodology when new data become available. The new version 2.1, compiled at 5 km interval, at 5 km altitude above the continents and at sea-level over the oceans, includes new datasets: (1) the complete digital aeromagnetic map of Brasil made available by ANP; (2) an improved version of the aeromagnetic map of Russia prepared by V-SEGEI; (3) the second version of the Antarctic Digital Magnetic Anomaly maP (ADMAP; Golynsky et al., GRL, 2018) which results from a remarkable international effort during and after the Second International Polar Year; (4) a new map of the Caribbean Plate and Gulf of Mexico (Garcia and Dyment, EPSL, 2021, 2022); (5) the updated Magnetic Anomaly Map of Eastern Asia prepared by the CCOP (MAMEA; Ishihara and Uchida, 2021); and (6) a new marine magnetic anomaly data compilation prepared by T. Ishihara and coworkers. The remaining data gaps are filled with a satellite anomaly model (Thebault et al., GRL, 2021). Long wavelengths of degree and order lower than 120 are filtered and replaced by those computed between order and degree 16 and 120 using the same satellite magnetic anomaly model from CHAMP and Swarm data. The new map will be presented and its significant improvements over the previous version discussed.

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JS03g - Probing the Earth’s Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Sub-continental lithospheric mantle and crustal structure of Fennoscandian shield mineral systems

DOI: 10.57757/IUGG23-3687 - LINK

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[2]Lulea Technical University, Geophysics, Lulea, Sweden
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[4]Slovak Academy of Sciences, Institute of Earth Sciences, Bratislava, Slovakia

The mineral system concept considers the processes and large-scale controlling structures involved in the generation, emplacement and preservation of mineral deposits, not just the characterisation of individual near surface regions of economic potential. Archean cratonic environments such as the Canadian shield, Gawler Craton - Australia, and the Fennoscandian shield are home to some the world’s largest known mineral reserves typically along their margins. Despite a long history of study, the processes responsible for generation and emplacement of these large mineral rsources remain equivocal, however, what has become clear is that much larger regional scale geophysical imaging of Archean cratons is required to understanding these systems. Sub-continental lithospheric mantle (SCLM) and crustal architecture which have traditionally been viewed as secondary considerations in understanding the distribution of major mineral deposits have recently been shown through the large scale approach employed in D-REx as fundamental in understanding the larger scale mineral system. Surface geologies and upper crustal structure are often broadly similar in endowed and lesser endowed terranes suggesting the difference in endowment level may result either from: a deeper burial depth of endowment beyond the depth resolution and/or depth of interest of more traditional exploration approaches; or differences in the deeper SCLM and mid-lower crustal evolution of these regions. The D-REx approach has allowed identification of the early earth history and processes responsible for the concentration of metals in the current uppermost crust of the Fennoscandian shield and identified key structural controls at SCLM depths indicative of near surface metal endowment.

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JS03g - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Whole of lithosphere and mineral systems connection - insights from new magnetotelluric arrays across the Gawler craton, South Australia

DOI: 10.57757/IUGG23-4806 - LINK

Stephan Thiel[1]
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Lithospheric cratons withstand significant tectonic events over time due to their strong rheology and buoyancy. The Archean-Proterozoic Gawler Craton, South Australia, experienced heightened tectonic activity between 2.0 and 1.4 billion years ago, leading to a metasomatised mantle signature and world-class mineral systems including iron-oxide copper gold (IOCG) deposits and gold deposits. While the various deposit styles are often hundreds kilometers apart, vast arrays of magnetotelluric (MT) data point to a common primary architecture, in which the deposits are ultimately linked to a common metasomatised mantle source. Along the eastern margin of the Gawler Craton, the IOCG deposits have been extensively imaged with MT, including the super-giant Olympic Dam deposit. Here, we present new magnetotelluric data across a 12.5 km array and two closely spaced profiles totalling ~ 400 new broadband MT stations, across the western margin of the Gawler craton. The new data reduces the 50 km site spacing from the existing AusLAMP (Australian Lithospheric Architecture Magnetotelluric Project) by a factor of four to increase the resolution of the resistivity structure from the lower to upper crust. The scale reduction will constrain the magma and fluid pathways in between Archean lithologies present in the crust beneath the survey area and inform the genesis of the prevailing gold and nickel-copper deposits throughout the western Gawler craton. The 3D models show unprecedented insight into fossilised pathways of Proterozoic fluid flux along the craton margin.

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JS03g - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Modelling of a high-resolution Moho geometry from a synthetic gravity field data for tectonic studies over southeastern Nigeria

DOI: 10.57757/IUGG23-0128 - LINK

Ojima Apeh[1,2], *Robert Tenzer*[1], *Elochukwu Moka*[2], *Emmanuel Onah*[2], *Elijah Ebinne*[2], *Victus Uzodinma*[2], *Francis Okeke*[2]
[1]*The Hong Kong Polytechnic University, Land Surveying and Geo-Informatics, Hong Kong, Hong Kong*
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Mapping of the Moho geometry could serve as an effective tool for visualization of the tectonic features/processes and their interactions beneath a region of interest. In this study, we employed a high-resolution (25″×25″ grid) tailored Bouguer gravity data to explore the mechanisms of tectonism beneath a highly rifted continental plate of the Southeastern Nigeria. Hence, we separated the Bouguer gravity data into shallow (high-pass) and deep (low-pass) gravity signals before carrying out gravimetric inversion. To obtain suitable estimates of gravimetric inversion parameters (reference depth and density contrast), we numerically computed and stochastically evaluated a seismically and our gravimetrically determined crustal thickness until a minimum RMS of their differences was achieved. Our obtained crustal thickness data range from 22 to 36 km with a stochastically determined optimal reference depth of 26 km and density contrast of 0.45gcm^{-3}. The crustal thickness map reveals a dense magmatic feature traversing the central portion of the study area in northeastern, southeastern, and southwestern directions leading to the thinning of the crust in those regions. We have been also able to refine and depict the lateral extent of the different sub-basins, ridges, crustal architecture, and the geophysical processes (magmatism, faulting/fracturing, mantle uplift, crustal thinning/thickening) of continental separation within the study area from our crustal thickness map. Considering the fine-scale discontinuity and continuity of tectonism revealed in our crustal thickness map, we conclude that a narrowing of two or more conjugate plates might have mainly occasioned those visible and complex geophysical phenomena.

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JS03g - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Crustal Architecture of sub-basalt structures of Deccan Volcanic Province, India

DOI: 10.57757/IUGG23-2566 - LINK

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The Deccan Volcanic Provinces (DVP) is one of the Largest Igneous Province (LIP) of the world covering an area of half a million sq. km in central and western India. Due to the blanketing by the lava flows the geology and tectonics of sub-basalt remain speculative both in terms of resources as well as hazards assessment. However, recent advances in instrumentation & processing methodology leading to refined interpretation techniques have contributed to a quantum jump in the application of geophysical techniques to sub-basalt exploration as well as understanding the crustal configuration. In this study, we have utilized ground geopotential data (gravity and magnetic) with constraints from other studies to look at the structures below the basaltic terrain. From the combined analysis of the geopotential data, we could delineate the extension of several lineaments/faults, schist belts, etc below the trap cover. For the first time, we have identified several NE-SW trending lineaments within the DVP cutting across the NW-SE lineaments and giving rise to block structural architecture within the DVP. To have a better insight into the rheological, thermal, and petrological details of the study area we have computed the moho depth using inversion of gravity data while the depth to the bottom of the magnetic sources was computed using the power spectral methods. Combined two-dimensional modeling along two profiles provided better insights into the structures below the traps. The results of these analyses will be presented.

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JS03g - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Geochemical signatures of the Volcano-sedimentary rocks of mauranipur-babina greenstone belt, bundelkhand craton, India: Implications for tectonic setting and depositional environment

DOI: 10.57757/IUGG23-0862 - LINK

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[2]Institute of Earth Science- Bundelkhand University-, Department of Geology, Jhansi- Uttar Pradesh, India
[3]Wadia Institute of Himalayan Geology-, Petrology & Geochemistry, Dehradun- Uttarakhand, India

The Bundelkhand Craton has a well-developed E-W trending Mouranipur-Babina Greenstone Belt (MBGB), which has excellent preservation of BIFs, cherts, sandstones, greywackes, quartzites, and associated komatiite-basalt-andesites. The pillow, massive basalts, komatiite basalts, andesites of Baragaon, BIFs of Saprar and Babina, chocolate-colored cherts from Babina, sandstones of Bhauti, fuchsite quartzites and metagreywackes from Swargeswarashram are studied for petrology and geochemistry to decipher the tectonic evolution of the Bundelkhand Craton. The CaO/Al_2O_3, $(Gd/Yb)_N>1$, positive Nb anomalies, La/Sm, La/Ta, Nb/Th, and high MgO contents (>20 wt.%) of the komatiite basalts reflect a mantle plume source for the early stage greenstone growth. Bimodal metavolcanics with tholeiitic to calc-alkaline affinity shows basalt-andesite-dacite-rhyolite differentiation trend in a convergent setting (arc-back arc), where partial melts are generated from thick metamorphosed basaltic crust after mantle plume. The metagreywackes, sandstones, and cherts are derived from felsic to mafic sources as indicated by their Cr_2O_3, TiO_2-Al_2O_3, and Zr, Th/Yb-Ta/Yb relationship. The BIFs of Saprar are characterized by low silica and high iron, whereas for Babina, the opposite is true. The Cu, Zn, Pb, V, Sr, and Ba contents of Babina BIF are very high compared to BIFs of Saprar, which in turn record high Sc, Cr, and Zr contents. ∑REE-Cu+Co+Ni, SiO_2-K_2O/Na_2O, and Cr-Ni discriminations infer that BIFs of MBGB are of Algoma type. Thus, the geochemical signatures of the volcano-sedimentary sequences strongly endorse Neoarchean plume-arc accretion tectonics in this greenstone belt, like other north-south trending greenstone belts of India.

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JS04a - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Hunga Tonga islands evolution from remote sensing and future detectability with Next Generation Gravity Satellites

DOI: 10.57757/IUGG23-4697 - LINK

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The Hunga Tonga Hunga Ha'apai (HTHH) islands have evolved since 2014, as we trace back through the SAR and multispectral satellite imaging of the Sentinels 1 and 2. The modulations of the outline of the islands are accompanied by mass changes, possibly detectable through a variation of the gravity field. These mass changes are the sum of the height changes of the emerging parts of the volcano, and the volume changes concealed below the ocean surface. The goal of the study is to define realistic mass changes that are associated to the evolution of HTHH, then to estimate the gravity changes in space and time, and finally estimate the sensitivity of observational methods to the gravity changes. Present ongoing efforts define the noise level in acquisitions of multi-satellite constellations carrying innovative instrumentation as quantum technology gravimeters or gradiometers [1,2]. The MAGIC mission planned for end of the 2020ties shall combine an inclined and polar pair of a GRACE-like mission to achieve a significant improvement in the recovery of the time variable gravity field. We find that the improvements of the future satellite missions should allow us to detect the subsurface mass changes generated by submarine volcanic activity, although the estimated mass changes for HTHH pose a challenge for the detectability. Next to HTHH we make a review of other known submarine eruptions and find that bigger volcanic mass changes are documented, which could be effectively observed.

References

[1] Migliaccio *et al.* (2023). *SurvGeophys*, https://doi.org/10.1007/s10712-022-09760-x

[2] Pivetta et al. (2022). *RemoteSensing*, https://doi.org/10.3390/rs14174278

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JS04a - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Geometry of volcanic systems with magnetotelluric soundings: results from land and marine magnetotelluric surveys during the 2018-2019 Mayotte seismovolcanic crisis

DOI: 10.57757/IUGG23-2731 - LINK

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A major seismovolcanic crisis has afflicted the islands of Mayotte, Comoros Archipelago, since May 2018, although the origin is debated. The region of Mayotte is composed predominantly of two main islands, namely, Grande Terre (363 km2) to the west and Petite Terre (11 km2) to the east. In May 2018, an offshore seismovolcanic crisis initiated approximately 50 km to the east of Mayotte; the crisis included the largest seismic event ever recorded in the Comoros with a Mw=5.9 and an estimated 5 km3 of lava was released from an eruptive site. Magnetotellurics (MT), which is sensitive to hydrothermal and/or magmatic fluids and can map the subsurface electrical resistivity structure, can provide insight by revealing the internal structure of the volcanic system. We report the results of a preliminary land and shallow marine MT survey performed on and offshore the island nearest the crisis. The 3D inversion-derived electrical resistivity model suggests that the island is underlain by a shallow ~500-m-thick conductive layer atop a deeper, more resistive layer, possibly associated with a high-temperature geothermal system. At depths of ~15 km, the resistivity drops by almost two orders of magnitude, possibly due to partial melting. Further petrophysical and geophysical studies are underway for confirmation and to map the geometry and evolution of the volcanic system.

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JS04a - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

ECS Awardee 2023: Geothermal anomalies preceding the 2021 Cumbre Vieja (La Palma, Spain) eruption

DOI: 10.57757/IUGG23-2883 - LINK

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Identifying the observables that warn of volcanic unrest and eruptions is one of the greatest challenges in natural hazard management. Recently, Girona et al., 2021 (https://www.nature.com/articles/s41561-021-00705-4), discovered that volcanic edifices may slightly warm in the years leading up to both phreatic and magmatic eruptions. This warming, or low-temperature (low-T) geothermal anomaly, was found by analyzing ~16 years of long-wavelength (~11 μm) thermal infrared radiance data recorded by the moderate-resolution imaging spectroradiometers (MODIS) aboard NASA's Terra and Aqua satellites. However, many questions remain open. For example: What is the link between the spatiotemporal distribution of low-T geothermal anomalies and subsurface gas transport? We address this question by updating the remote sensing-based methodology proposed by Girona et al. (2021), by testing different physics-based, finite element (COMSOL) simulations to model gas and heat transport through volcanic edifices, and by using the 2021 Cumbre Vieja (La Palma, Spain) eruption as a case study. Our remote sensing-based analysis reveals that the 2021 Cumbre Vieja eruption was preceded by ~10 years of low-T geothermal anomalies in the crater of Taburiente caldera, located 10-to-12 km to the north of the 2021 eruptive center. Moreover, our models suggest that the pre-eruptive, low-T geothermal anomalies were possibly controlled by the latent heat released during the subsurface condensation of magmatic and/or hydrothermal H_2O. The possibility of tracking the spatiotemporal distribution of low-T geothermal anomalies using satellite data opens new horizons to indirectly detect the pre-eruptive transport of hot gas towards the surface and potentially better forecast eruptions from space.

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JS04a - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Evidence of a low-velocity-zone in the upper mantle beneath Cumbre Vieja volcano (La Palma, Canary Islands) through receiver functions analysis.

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The receiver function analysis (RF) is a well-established method to investigate the crustal and upper mantle structure in different geodynamic settings. It is highly sensitive to seismic discontinuities and provides information about P- and S-wave velocities beneath a seismic station.

This work aims to study the crust and the upper mantle of La Palma Island up to 50 km of depth by using RF analysis. La Palma is one of the youngest oceanic volcanic islands of the Canary archipelago, with a complex internal structure that makes applying conventional RF challenging. The island was affected in 2021 by the devastating Tajogaite eruption which occurred on the Cumbre Vieja volcano.

For this study, we obtained RFs of five stations using multi-taper deconvolution. After that, we applied the transdimensional approach of Bodin et al. (2012) to determine 1D profiles of P- and S-wave velocities and the probability of a discontinuity beneath each station.

Each 1D model was interpolated to build a N-S trending seismic section that allowed us to correlate the different discontinuities. We observe a Low-Velocity Zone in the upper mantle beneath the Cumbre Vieja volcano and four different layers with a significant change in their Vp/Vs ratios. These results are compared with the seismicity recorded beneath the island from 2017 until the pre-eruptive phase of the Tajogaite eruption. Hypocenters are mainly located at the base of the crust (10-15 km deep) and in the upper mantle (20-30 km deep), possibly related to the presence of two subcrustal magmatic reservoirs.

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JS04a - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Crater evolution and late complex tensile fracturing during the 2021 eruption at Cumbre Vieja, La Palma

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Volcanic eruptions are often preceded by episodes of inflation and emplacement of magma along tensile fractures, forming dikes or sills. Here, we present evidence for crater alignments and for a complex tensile fracture dissecting part of the eruption cone, during the very late stages of the Cumbre Vieja eruption. We use satellite radar amplitude image observations, together with photogrammetrically processed drone and time-lapse camera data, to determine scale and complexities associated with the late fracturing event. In a rapid response task force we acquired in-situ data, which we complement by the use of analog models to show that formation of the tensile fractures are strongly influenced by topography, diverging at topographic highs and converging at topographic lows. The observations at the late eruption phase and from our models are of importance for understanding tensile fracture sets at the already pronounced volcano topography of La Palma, and allow speculation of a shallow topographic driver responsible for a localized dike propagation.

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JS04b - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

AVERT: An open system for multi-parameter volcano monitoring

DOI: 10.57757/IUGG23-4832 - LINK

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Volcanic eruptions pose a major threat to many communities around the world. Yet openly accessible, real-time, multi-parameter data are available only for a few volcanic systems. While efforts are made to tackle the significant logistical and financial challenges involved with improving instrumentation at remote systems, it is important to also ensure a robust and easy-to-implement pathway from the point of acquisition to public repositories. An effective stream of multi-parameter observations from active volcanoes will drive the development of the next generation of physics- and data-based eruption forecast models. Here we report the development and field testing of a multi-parameter, real-time, open-data volcano monitoring system through our collaborative project AVERT: Anticipating Volcanic Eruptions in Real-Time.

The AVERT system has been deployed on Cleveland (open-vent) and Okmok (closed system) volcanoes—situated in the remote Aleutian arc—in partnership with the Alaska Volcano Observatory. Novel instruments, e.g. continuous fluxgate magnetometers, synchronised visible and infrared cameras, and soil probes for temperature and CO_2 flux, were installed in addition to seismic, GNSS, and gas sensors. A low-power single-board computer coordinates data archiving and telemetry—via radio and various satellite pathways—at each node in the network. In-situ analysis of data facilitates optimised data telemetry and lower latency detections of changes in the state of volcanic unrest. The small form factor, modular design of the system enables rapid deployment and straightforward incorporation of a wide variety of instruments into the data telemetry system. Design plans and software will be available to the community following successful proof-of-concept testing.

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JS04b - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Infrasonic noise from lava eruptions at Nyiragongo volcano, D.R. Congo

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During eruptions, volcanoes produce air-pressure waves inaudible for the human ear called infrasound, which are very helpful for detecting early signs of magma at the surface. Compared to violent ash-rich explosions, recording more discreet atmospheric disturbances from effusive eruptions remains a practical challenge. Wind and human activity are other powerful sources of unwanted infrasound noise masking volcanic ones. At Nyiragongo volcano (D.R. Congo), close to a one-million urban area, the drainage of the world's largest lava lake concomitant with short-duration lava flows on its flank and the renewal of an effusive eruption within its crater a few months later were a series of major volcanic events in 2021, all monitored with infrasound sensors. First, we explore these records for characterizing the temporal and spatial evolution of the flank eruption on May 22, 2021. In a second step, we show evidence of the infrasonic rumbling of a nascent lava lake starting a few months later detected up to the volcano observatory facilities in Goma city center about 17 km from Nyiragongo's crater. These results show remarkable local recordings of eruptive infrasound from rural and city-based stations and have significant implication for optimizing future monitoring efforts in a harsh field environment.

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JS04b - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Magnetotelluric imaging and monitoring of Villarrica volcano, Southern Andes of Chile.

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Villarrica volcano, in the Southern Andes of Chile, is at the top of the Specific Threat Ranking for Active Volcanoes, published by the National Geology and Mining Service of Chile during 2019.
In recent years, broadband magnetotelluric measurements have been carried out around this volcano, to study its internal structure. Combining these data with information obtained from long-period magnetotelluric stations, an electrical resistivity model for this volcano and its surroundings is presented, identifying highly conductive anomalies down to depths of 15 km below sea level.The model obtained and presented in this work is complementary to the project of monitoring geophysical variables such as electrical resistivity in volcanoes, through the installation of permanent magnetotelluric stations.
Villarrica volcano is now the first volcano with magnetotelluric monitoring in Chile, in a collaborative project between the University of Chile and the National Geology and Mining Service (SERNAGEOMIN), through the Southern Andes Volcano Observatory (OVDAS). Details about the installation, measurements and first results of this experiment will be part of this presentation.

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JS04b - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Probing the 4D evolution of active magmatic systems through magnetotelluric monitoring: Mount St Helens as an illustrative example

DOI: 10.57757/IUGG23-1246 - LINK

Graham Hill[1], Max Moorkamp[2], Yann Avram[3], Colin Hogg[4], Sofia Gahr[2], Kathi Mateschke[2], Adam Schultz[5], Esteban Bowles-Martinez[5], Jared Peacock[6], Gokhan Karcioglu[1], Chaojian Chen[2], Corrado Cimarelli[7], Luca Caricchi[8], Yasuo Ogawa[9], Duygu Kiyan[4]
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Detection of geophysical signatures associated with a geologic event, such as a volcanic eruption, is key to understanding the underlying physical processes and making an accurate hazard assessment. Magma reservoirs are the main repositories for eruptible magma, and understanding them requires the ability to detect and interpret changes in the magmatic system from surface measurements. Traditionally, monitoring for these changes has been done with seismic and geodetic approaches, both of which require dynamic 'active' changes within the magmatic system. Neither of these techniques is sensitive to the petrology or temperature of the magma though. Thus, additional monitoring techniques able to detect 'static' phase changes in the evolving magma and the thermal structure of the magma reservoir are needed. The magnetotelluric method, measures subsurface electrical properties and is sensitive to both 'magma on the move' and petrological changes that occur within the magma reservoir. Using Mount St Helens where a detailed magnetotelluric survey was completed during the most recent dome building eruptive phase 2005-06, and is now in a period of quiescence, we compare the original measurements to repeated measurements in the same locations in 2022 to develop temporal analysis approaches required for monitoring. In addition to the repeat campaign we have deployed 4 long-term continuous monitoring stations with telemetry to local servers. First, qualitative, comparisons of the data from different time periods indicate some significant changes in subsurface conductivity. We present an overview of the newly acquired data and the monitoring setup and discuss where the most significant changes occur.

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JS04b - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Electromagnetic monitoring of volcanic systems, preliminary comparative phase tensor analysis of Mount St Helens magnetotelluric data

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Gokhan Karcioglu[1], Graham Hill[1], Max Moorkamp[2], Yann Avram[3], Colin Hogg[4], Sofia Gahr[2], Kathi Mateschke[2], Adam Schultz[5], Esteban Bowles-Martinez[5], Jared Peacock[6], Chen Chaojian[2], Corrado Cimarelli[7], Luca Caricchi[8], Yasuo Ogawa[9], Duygu Kiyan[4]
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The Cascade arc runs from Southern British Columbia through Northern California and developed by the subduction of the Juan de Fuca plate beneath North America. Among the volcanoes of the Northern Cascades, Mount St Helens (MSH) is the most active. Inter-connected melt within the underlying magmatic systems of volcanic regions allow identification of the system via Magnetotelluric (MT) imaging due to the sensitivity of the method to electrical conductivity. Time variance of the properties of the melt due to changes in eruptive activity may result in significant conductivity changes that can be identified with continuous MT monitoring. Galvanic distortions resulting from the small near-surface conductivity variations may can be difficult to separate from the expected subtle observational differences. However, impedance phase relations in MT are free of these galvanic distortions. Thus, by exploiting changes in the phase response (the MT Phase tensor), it is possible to identify the temporal conductivity changes associated with changes occurring within the magmatic system.
Prior MT results in the Washington cascades show a significant conductive anomaly underneath the MSH attributed to be partial melt supplying the volcano. With the aim of revealing conductivity changes beneath MSH, both a campaign style reoccupation of measurements completed during the 2004-2008 dome building eruption, and installation of four ‘continuous’ monitoring MT stations has been completed. Among the new MT dataset, a preliminary comparative phase tensor analysis of 56 repeated measurements identifies conductivity changes at frequencies that correlate the depth of the partial melt within the magmatic system.

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JS04b - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Improved Estimates of Crustal Magmatic Storage at Arc Volcanoes Through Seismic Receiver Functions

DOI: 10.57757/IUGG23-4789 - LINK

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Recent research points to complex, multi-layered, transcrustal magmatic systems beneath volcanoes. But constraints on depths of magma storage in the mid-to-deep crust beneath volcanoes remain an enigmatic target. At volcanic arcs, magmatic processes at these depths are a critical link between the input from the slab and mantle wedge, the emplacement processes that build and alter arc crust, and the shallow crustal reservoirs that drive eruptions. Magmatic storage depths and pathways may be governed by a variety of properties, including volatile content, crustal stress regime, prexisting structures, and more. To better understand how these variables may impact arc volcano processes, we must employ techniques that allow us to characterize magma storage depths at volcanoes globally. Here, we investigate receiver functions as a technique to provide systematic, first-order constraints on magma storage depths in the mid-to-deep crust using data from the Alaska-Aleutian island arc as a case study. Receiver functions are sensitive to abrupt seismic velocity boundaries, and have detected low velocity zones in the crust interpreted as magmatic-mush systems at Akutan and Cleveland, two Alaska-Aleutian arc volcanoes. They do not rely on the presence of local seismicity, do not require a wide-aperature array to image the whole crust, and can be analyzed at volcanoes with relatively few (< 4) local instruments. We present results of the application of this technique across the Alaska-Aleutian arc, and examine along-arc trends in receiver function properties.

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JS05a - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

A review of the contribution of real-time GNSS to disaster prevention and mitigation in Japan

DOI: 10.57757/IUGG23-1032 - LINK

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Rapid monitoring of large earthquakes, associated tsunamis, volcanic eruptions, and other phenomena is extremely important for understanding the underlying phenomena, as well as for disaster prevention and mitigation. In Japan, the Geospatial Information Authority of Japan (GSI) operates a continuous nationwide GNSS network (GEONET) across Japan. Based on the lessons learned from the 2011 Tohoku-Oki earthquake, the GSI and Graduate School of Science, Tohoku University, have jointly developed a new crustal deformation analysis system using GEONET data for quasi real-time earthquake size estimation, known as the GEONET analysis system for rapid deformation monitoring (REGARD) (Kawamoto et al. 2016, 2017). The results of REGARD is used by the JMA as supporting information when issuing tsunami warnings/advisories. The fault models of REGARD were also adopted as sources to estimate tsunami inundation, and resulting damage. The system has been adopted as part of the Disaster Information Systems (DIS) operated by Japan’s Cabinet Office (Musa et al. 2018; Ohta et al. 2018) and will use the generated information for the initial governmental response after tsunamigenic earthquakes. In the presentation, the roles of real-time GNSS in disaster prevention and mitigation will be discussed, focusing on these developments of REGARD and others.

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JS05a - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

EWRICA project: Rapid earthquake source and impact assessment augmented by real-time GNSS in the Mediterranean

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High-precision real-time GNSS have recently expanded to monitoring and early detection of natural hazards. German research project EWRICA (Early-Warning and Rapid ImpaCt Assessment with real-time GNSS in the Mediterranean) funded by the national Ministry for Education and Research aims for the prototype implementation of the GNSS-augmented seismic source inversion and rapid impact assessment in the seismically active regions of Mediterranean. The project runs in close cooperation with partners operating high-rate GNSS networks RING (Italy) and NOANET (Greece). An overarching goal is to compute robust local ground motion models shortly after an earthquake to assess areas of strong shaking as well as secondary effects such as tsunamis and landslides. The four work packages - (1) real-time processing of coseismic displacements (RT-multi GNSS with regional augmentation, streamed in miniSEED format via SeedLink server, optionally joint processing with collocated accelerometers); (2) fast source inversion (Bayesian moment-tensor solution with Pyrocko tools); (3) rapid impact assessment (neural network predictions of ground motion maps with uncertainties, also coupled to probabilistic tsunami forecasting PTF at INGV); and (4) system prototype -- end up with an operational system prototype to demonstrate the full operational processing chain by hindcasting selected historical (e.g., 2016 M6.2 Norcia; 2020 M7 Samos) and synthetic event scenarios. EWRICA may serve as a blueprint for other regions of the world: currently EWRICA's tools are being tested for application in Indonesia, together with the colleagues from the Geospatial Agency (BIG) and from the national tsunami warning center InaTEWS.

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JS05a - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Reliable co-seismic displacement from tightly integrated processing of GNSS and Accelerometers

DOI: 10.57757/IUGG23-1534 - LINK

Weiliang Xie[1,2], Xinyuan Jiang[1,2], du Shi[1,2], Maorong Ge[1,2], Harald Schuh[1,2], Avallone Antonio[3], Babeyko Andrey[1]
[1]German Research Centre for Geosciences GFZ, Geodesy, Potsdam, Germany
[2]Technical University of Berlin, Geodesy, Berlin, Germany
[3]National Institute of Geophysics and Vulcanology, Centro Nazionale Terremoti, Grottaminarda, Italy

Integrated processing of high-rate GNSS and accelerometer data can overcome the disadvantage of each individual sensors and to increase the quality of derived co-seismic displacement. However, the contribution of accelerometer is usually underestimated by estimating baseline shifts epoch-wise which in fact happened very rarely. To take full advantage of both sensors, we propose a sliding window based Kalman filter to detect baseline shifts according to the disagreement of GNSS and accelerometer data and to estimate only the detected baseline shifts. The relationship of the window width, minimal detectable baseline shift and the displacement accuracy is investigated. The performance of the proposed approach is demonstrated by datasets collected during Samos Island earthquake (Mw 7.0, 30th October 2020). The results show that the baseline shifts in accelerometers can be precisely detected and estimated according to the very good agreement of the displacement integrated from accelerometer data after applying baseline shift corrections and that estimated from high-rate GNSS. Furthermore, the baseline corrected accelerometer data provides tight and reliable constraints on position and velocity to facilitate correct PPP ambiguity resolution. Thanks to the proposed approach, the complementary of GNSS and accelerometers is fully employed, consequently the co-seismic displacements of the tightly integrated processing are significantly improved.

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JS05a - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Making GNSS products interoperable in seismology: the integration of real-time Precise Point Positioning into SeisComP

DOI: 10.57757/IUGG23-4232 - LINK

Angelo Strollo[1], Andres Heinloo[1], Andrey Babeyko[1], Maorong Ge[2], Xinyuan Jiang[2], Bernd Weber[3], Andreas Hoechner[3]
[1]GFZ German Research Centre for Geosciences, Geophyiscs, Potsdam, Germany
[2]GFZ German Research Centre for Geosciences, Geodesy, Potsdam, Germany
[3]gempa GmbH, r&d, Potsdam, Germany

Interoperability of data and products among disciplines is becoming a key aspect within the scientific community to allow the optimal integrated exploitation of data, taking advantage of modern real-time work-flows using also AI techniques. Within the EWRICA project, aiming at creating robust local ground motion models shortly after an earthquake to assess secondary effects such as tsunamis and landslides, one of the tasks focussed on integration of near-field seismo-geodetic data into real-time source inversion. To enable this task, Real-Time Precise Point Positioning (RT-PPP) data have been converted to miniSEED records on the fly by using a tailored plugin for SeisComP developed within the project. The real-time data in GFZ Displacement Real-Time (GDRT) format have been mapped to miniSEED channels as described in the SeisComP documentation [1]. The initial mapping has been defined considering also one additional use case implemented in the TURNkey project where RT-PPP data were generated from a newly developed standalone instrument. RT-PPP has been integrated in the data flow and sent out to clients via seedlink for processing in the known data and metadata format enabling faster and improved assessment of seismic moment, hypocentre and rupture kinematics.
In this presentation we introduce the gdrt_plugin released for the first time in June 2022 with the SeisComP v5.0.0 [2], we outline the initial process of mapping the GNSS products to existing data and metadata formats and would welcome discussions about further integration in seismology through the FDSN.

[1] https://www.seiscomp.de/doc/apps/seedlink.html#seedlink-sources-gdrt-label
[2] https://github.com/SeisComP/seiscomp/releases/tag/5.0.0

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JS05a - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Ionospheric HF Doppler indication of GNSS positioning errors

DOI: 10.57757/IUGG23-1616 - LINK

Jaroslav Urbar[1], Luboš Rejfek[1], Jaroslav Chum[1], Vladimir Truhlik[1], Jan Rusz[1], Jiří Baše[1], Jakub Horký[1], Jiří Šimůnek[1], Zbyšek Mošna[1], Daniel Kouba[1], Dalia Obrazová[1]
[1]Institute of Atmospheric Physics CAS, Ionosphere and Aeronomy, Prague, Czech Republic

The HF Doppler ionospheric measurements can along with identification of medium scale wave activity provide also estimation of the level of the related GNSS positioning errors.
The paper demonstrates the rise of GNSS positioning error with increasing wave activity at ionospheric heights and with changing parameters representing ionospheric waves as measured by Czech Continuous Doppler Sounding Systems (CDSS) deployed around Europe, Argentina, South Africa and Taiwan.
Results using state-of-the-art Septentrio GNSS receivers applying various combinations of GNSS frequencies (L1&L2&L5+SBAS as its accuracy depends on the allocated signal bandwidth and modulation schemes) confirmed in all those scenarios correlation of positioning precision with the Medium-scale Traveling Ionospheric Disturbance (MSTID) activity-related ionospheric disturbances as monitored by the CDSS.
The most significant relation was found between the CDSS Doppler frequency-shift measurements (dF), even stronger than one naturally occurring during indications of ionospheric SpreadF.

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JS05b - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

GSeisRT: regional GNSS point positioning for wide-area seismic monitoring in real time

DOI: 10.57757/IUGG23-5024 - LINK

Jianghui Geng[1], *Shaoming Xin*[1], *Kunlun Zhang*[1]
[1]*Wuhan University, GNSS Research center, Wuhan, China*

GSeisRT software developed by Wuhan University is dedicated to real-time GNSS data processing, and it is free and open for the science community under mutual agreement. GSeisRT consists of a server end and a client end. GSeisRT server can use a regional GNSS network to estimate satellite clocks and phase biases independently or access IGS (International GNSS Service) real-time clock and orbit products to estimate satellite phase biases, which is more flexible and compatible with different data scenarios. Then GSeisRT client can realize multi-GNSS (GPS/GLONASS/GALILEO/QZSS/BeiDou) precise point positioning with ambiguity resolution (PPP-AR) and achieve centimeter-level to sub-centimeter-level precision in real time based on the products of GSeisRT server or IGS real-time service. The acquisition of real-time position can be applied to scenarios such as earthquake displacement monitoring, which is necessary and socially significant. In addition, GSeisRT will provide a lite version of the client with a user interface that can estimate and display the ionospheric delay of multi-GNSS satellites in real time. Considering user privacy and data security, GSeisRT could not only support the processing of public data streams but also be deployed in a private operating environment to process proprietary data streams, then users' data security and autonomy can be guaranteed.

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JS05b - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Real-time GNSS earth surface displacement monitoring using PPP with regional augmentation and its implementation in the EWRICA project

DOI: 10.57757/IUGG23-3507 - LINK

Xinyuan Jiang[1,2], *Weiliang Xie*[1,2], *Shi Du*[1,2], *Maorong Ge*[1,2], *Antonio Avallone*[3], *Andrey Babeyko*[4]
[1]*German Research Centre for Geosciences GFZ, Geodesy, Germany, Germany*
[2]*Technical University of Berlin, Planning Building Environment, Berlin, Germany*
[3]*National Institute of Geophysics and Vulcanology, National Earthquake Centre, Rome, Italy*
[4]*German Research Centre for Geosciences GFZ, Geodynamic Modelling, Germany, Germany*

Recent advances in high-precision real-time applications of the Global Navigation Satellite System (GNSS) have expanded to monitoring and early detection of natural hazards. The real-time Precise Point Positioning with Regional Augmentation (PPP+RA) technique has become increasingly popular for providing rapid and precise ground displacement information due to the availability of real-time precise GNSS satellite orbit and clock products, as well as high-rate observations. In this contribution, we implemented the PPP+RA technique to the Early-Warning and Rapid Impact Assessment with real-time GNSS in the Mediterranean (EWRICA) project for earth surface displacement monitoring. A real-time GNSS precise positioning system is developed for the project. About 80 stations from the RING network in Italy are used to evaluate the performance the system. It's worth noting that more than half of the receivers in the RING network are LEICA receivers that support GPS only. We use GFZ's real-time precise satellite orbit and clock products for the data processing. The results show that the daily averaged accuracy of PPP+RA is 1.08 cm, 1.15 cm, and 3.20 cm in the east, north, and up directions, respectively, with a Time To First Fix (TTFF) of 1.1 minutes. Additionally, the system provides short-term relative positioning accuracy within 10 minutes, with a precision of a few millimetres, demonstrating its capability to detect even slight ground movements in real-time.

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JS05b - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Real-time GNSS @RING: from data acquisition to data analysis

DOI: 10.57757/IUGG23-3625 - LINK

Antonio Avallone[1], *Ciriaco D'Ambrosio*[2], *Luigi Falco*[2], *Xinyuan Jiang*[3], *Maorong Ge*[3], *Weiliang Xie*[3], *Andrey Babeyko*[4], *Gianpaolo Cecere*[2], *Roberto Devoti*[5], *Nicola Angelo Famiglietti*[2], *Carmine Grasso*[2], *Grazia Pietrantonio*[5], *Annamaria Vicari*[2]
[1]*Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti/Sezione Irpinia, Roma, Italy*
[2]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione Irpinia, Grottaminarda AV, Italy*
[3]*GFZ German Research Centre for Geosciences, Sect. Space Geodetic Technique, Potsdam, Germany*
[4]*GFZ German Research Centre for Geosciences, Sect. Geodynamic Modeling, Potsdam, Germany*
[5]*Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Roma, Italy*

The INGV RING research infrastructure is based on a permanent GNSS network developed to measure deformation at different spatial and temporal scales in the Mediterranean region. The network (http://ring.gm.ingv.it/) consists of ~250 real-time transmitting remote sites, using standard RTCM format, towards the Irpinia acquisition centres (Southern Italy). Data streaming is managed by a Ntrip Caster (https://igs.bkg.bund.de/ntrip/bkgcaster), whose sourcetable is synchronized with the RING database, thus guaranteeing reliable metadata for the analysis. Within the EWRICA project, the real-time data analysis is performed by using the RTPPP software (Ge et al.,2012) that provides different Precise Point Positioning products with increasing accuracies (standard PPP, PPP-AR and PPP-RA). On 24-h data, the ambiguity resolution (PPP-AR) and the regional augmentation (PPP-RA) allows accuracies of ~1 cm and ~3 cm for the horizontal and vertical components, respectively, at the best sites. Using shorter sliding windows (i.e. 60 s or 120 s, thus simulating a real-time situation), the accuracies are ~0,5 cm and ~1 cm for horizontal and vertical components, respectively. We also tested a homemade algorithm able to detect co-seismic static offsets in real-time in a simulated real-time strategy. The first results make the RING real-time solutions a potential contribution to be tested in earthquake and tsunami warning systems in Italy and surrounding regions. We will show the RING architecture, from the data to the PPP results, an evaluation of the uncertainties, and some examples of offset detection for recent earthquakes.

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JS05b - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Real-time monitoring surface deformation in Indonesia

DOI: 10.57757/IUGG23-2217 - LINK

Yan Anugrah Rahmawan[1], Gatot Haryo Pramono[1], Mohamad Arief Syafii[2], Xinyuan Jiang[3], Maorong Ge[3]
[1]Badan Informasi Geospasial, Center for Geodesy and Geodynamic Control Network, Cibinong, Indonesia
[2]Badan Informasi Geospasial, Base Geospatial Information, Cibinong, Indonesia
[3]German Research Centre for Geosciences GFZ, Geodesy, Potsdam, Germany

Real-time monitoring of earthquake-triggered surface deformation is becoming required to characterize the effect of an earthquake, either transient or permanent deformation. Indonesia as a country located in the active deformation region, through Geospatial Information Agency (BIG) has built 397 Real-Time Global Navigation Satellite Systems (RT-GNSS) stations that can be used to observe this phenomenon. The availability of RT-GNSS stations motivates us to provide real-time surface deformation information using the appropriate RT-GNSS processing method. We implement Precise Point Positioning with Regional Augmentation correction (PPP-RA) for stations if there are sufficient regional corrections, and Precise Point Positioning with Ambiguity Resolution (PPP-AR) otherwise. The result shows from Kota Fajar station in Sumatera Island (CKTF), the accuracy can be achieved at ± 1.4 cm, ± 1.8 cm, and ± 6.5 cm for the North, East, and Up components, respectively. we use the earthquake location information produced by Indonesia Tsunami Early Warning System (InaTEWS) operated by the Meteorological, Climatological, and Geophysical Agency (BMKG) to automatically collect the nearby stations from the epicenter. Then, we compute the displacement from each of its stations every second when the earthquake occurred. As a result, we can detect the transient deformation of the Banda Sea earthquake 7.6 Mw at depth of 108 km on January 9, 2023, with a maximum dynamic displacement at the nearest station to the source is 6.6 cm in the North-South direction and 8.7 cm in the East-West direction. This result suggests that this system is effective in displacement detection due to earthquakes.

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JS05c - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

GNSS tsunami early warning for the South Pacific

DOI: 10.57757/IUGG23-1252 - LINK

John L. LaBrecque[1]
[1]*University of Texas, Center for Space Research, West Palm Beach, USA*

The IUGG Commission on Geophysical Risk and Sustainability will join other national and international organizations to support a Coordinating Group for the development of a GNSS based Early Warning System (GTEWS) for the Oceania Region of the South Pacific. I will examine the state of GTEWS technology, its motivation, and the planning underway to explore the development of GTEWS for the South Pacific Region.

The IUGG 2015 General Assembly Resolution #4 called upon IUGG membership to work toward the implementation of a Pacific GTEWS as an augment to existing tsunami warning systems. The Group on Earth Observation (GEO), the UN International Committee on GNSS (ICG) and 17 agencies from 12 countries have joined the IUGG in calling for the implementation of GTEWS. Currently GTEWS are prototype national systems. A Pacific Basin system remains elusive largely due to the reluctance to share mesoscale real time GNSS data and the need for station upgrades.

The IUGG, GEO and the ICG will address these challenges through a cooperative effort amongst the nations of the South Pacific, international and national organizations, and the private sector. Australia and New Zealand are operating high quality real time GNSS networks and analysis centers. However, there is little intra-regional networking amongst the nations of Oceania. We seek a regional GTEWS network that will serve as a prototype for the development of a Pacific-wide GTEWS capability. (Ref: GTEWS 2017)

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JS05c - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Using GNSS receiver as a tsunami monitoring supplement: A case study of the 2023 M7.8 Turkiye earthquake

DOI: 10.57757/IUGG23-1721 - LINK

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Over the past years, with the rapid progress of Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) technique, near-shore geodetic GNSS receivers have been attempted to retrieve dynamic sea-level variation induced by storm surges and tsunamis. As the largest event since 1939, the 2023 M7.8 Turkiye earthquake not only caused terrifying building collapses on land but also generated observable tsunamis in the sea as recorded by coastal tide gauges. In this study, we thus try to verify the performance of GNSS-IR sea-level retrieval for tsunami monitoring based on GNSS data from IGS and TPGN(Turkish Permanent GNSS Network). Our preliminary findings show that, in spite of a continental strike-slip rupture, a tsunami with 30 cm wave height, following days of ocean resonance, is clearly seen by GNSS-IR, consistent with nearby tide gauge records. Furthermore, we also perform a finite source inversion to explore whether a submarine landslide contributes to the tsunami.

Our work demonstrates the capability of GNSS-IR for detecting medium and small tsunamis accurately. In fact, such geodetic GNSS receivers have been now well-deployed for co-seismic displacement monitoring and fast earthquake source characterizing for tsunami early warning in many places in the world. If more receivers can be installed near-shore, without extra operational costs, such a network will extend our tsunami observation power and improve the robustness of the tsunami early warning system.

Over the past years, with the rapid progress of Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) technique, near-shore geodetic GNSS receivers have been attempted to retrieve dynamic sea-level variation induced by storm surges and tsunamis. As the largest event since 1939, the 2023 M7.8 Turkiye earthquake not only caused terrifying building collapses on land but also generated observable tsunamis in the sea as recorded by coastal tide gauges. In this study, we thus try to verify the performance of GNSS-IR sea-level retrieval for tsunami monitoring based on GNSS data from IGS and TPGN(Turkish Permanent GNSS Network). Our preliminary findings show that, in spite of a continental strike-slip rupture, a tsunami with 30 cm wave height, following days of ocean resonance, is clearly seen by GNSS-IR, consistent with nearby tide gauge records. Furthermore, we also perform a finite source inversion to explore whether a submarine landslide contributes to the tsunami.

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JS05c - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

Integration of Real-Time Precise Point Positioning (RT-PPP) into Indonesian Tsunami Early Warning System (InaTEWS)

DOI: 10.57757/IUGG23-3796 - LINK

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[1]*Badan Informasi Geospasial, Center for Geodesy and Geodynamic Control Network, Cibinong, Indonesia*
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[3]*Gempa Gmbh, Gempa Gmbh, Potsdam, Germany*
[4]*German Research Centre for Geosciences GFZ, Geophysics, Potsdam, Germany*

Full integration of new data types into Indonesian Tsunami Early Warning System (InaTEWS) is among the enhancements being pursued at BMKG. Leveraging on external projects and partnership Real-Time Precise Point Positioning (RT-PPP) data from BIG have been integrated in the processing chain at BMKG. This GNSS data product has the potential contribute to faster and more accurate scenario selection and validation in case of large tsunamigenic events. Real-time waveforms displacement obtained with the method of Precise Point Positioning with Regional Augmentation correction (PPP-RA) and Precise Point Positioning with Ambiguity Resolution of the RT-PPP-Client, is thus acquired in SeisComP via a dedicated seedlink plugin developed within the project of Early Warning and Rapid ImpaCt Assessment (EWRICA) in the Mediterranean. Once integrated into SeisComP precise point positioning time series are integrated into the processing pipeline of the BMKG. We have successfully integrated RT-PPP processed by Geospatial Information Agency (BIG) into InaTEWS which is managed by the Meteorological, Climatological, and Geophysical Agency (BMKG). Next, waveforms will be used to improve and speed-up the earthquake parameter determination for large tsunamigenic events.

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JS06a - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Building probabilistic quasi-geology models and mapping mineral resources using joint inversion and geology differentiation

DOI: 10.57757/IUGG23-4333 - LINK

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Multiple data sets are typically collected in an airborne survey. The standard way of interpreting multiple airborne data sets is to invert them separately to obtain a set of physical property models, e.g., a density contrast and a susceptibility model. There are two issues with this approach. First, it does not make use of the complementary information contained in different data sets. Secondly, it is not straightforward to interpret multiple physical property models in terms of geological structures and compositions. We propose a new workflow to integrate the information from multiple geophysical data sets and prior geology information, if available, into a 3D quasi-geology model. This new workflow has two components: mixed Lp norm joint inversion and geology differentiation. Joint inversion allows for the reconstruction of structurally consistent physical property models. Geology differentiation is a process of classifying the recovered physical property values into distinct classes, each of which is characterized by a unique range of physical property values and can be interpreted as an individual geological unit. We have applied this workflow to a set of airborne geophysical data over the Decorah area in northeast Iowa, USA, and successfully created a probabilistic quasi-geology model that informs the geological structures and compositions in this area. The workflow has also been applied to the multiple airborne data sets collected over the QUEST project area in British Columbia, Canada, to help map prospective areas of mineral resources.

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JS06a - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

MT investigations to image thermal fluids in and around an active strike-slip fault near Annecy (France)

DOI: 10.57757/IUGG23-4398 - LINK

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Geothermal energy is an attractive renewable energy; however, its exploitation requires a sound knowledge of the nature, quality and boundaries of the reservoir to evaluate the resource potential and reduce the risk of induced seismicity. The purpose of this project is to use broad-band magnetotelluric (MT) data to investigate a medium-enthalpy geothermal zone in the region of Annecy, France. In this pre-alpine area, karstic limestones constitute a deep aquifer (up to ~2 km) intersected by the Vuache fault, an active strike-slipe fault where a M5.3 earthquake occurred in 1996.

A data set of 27 MT sites was acquired, with generally all 5 components measured. Data quality was mostly satisfactory up to 3 Hz and sometimes up to 1 s. Major problems were related to the presence of electromagnetic noise in this urbanized region, mitigated by the careful use of advanced processing methods (FFMT). For the 3-D inversion required by the data (phase tensors, WAL, topography), we have chosen a joint inversion of induction vectors, phase tensors and off-diagonal impedances (previously corrected for static shift with help of phase tensor inversion and few TDEM measurements). This allowed us to obtain a suitable 3D model using the ModEM inversion code, explaining all three data types reasonably well.

We aim at the integration of the obtained resistivity models with already existing results (seismic reflection, borehole information) into a geological model, which will be used within re-inversion of the MT data by turning off the smoothing across interfaces detected by seismic reflection.

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JS06a - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

A comparison of structurally coupled and constrained joint inversion of magnetotelluric data and teleseismic receiver functions using multiobjective swarm intelligence

DOI: 10.57757/IUGG23-2875 - LINK

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In recent years, joint inversion of magnetotelluric (MT) and seismological receiver function (RF) methods has provided valuable information about crustal structures and demonstrated a complementary tool. Joint inversion of such datasets that are not well correlated physically has been generally applied as structurally coupled in the literature. These are based on constraining the directions of parameter changes by a spatial regularization operator and placing their spatial changes at similar positions. However, the electrical conductivity and seismic velocity, which are the model parameters for MT and RF, may have different characteristics for the changes in the crustal zone, such as porosity, permeability, and temperature, and the unpredictable relationship between these parameters prevents full correlation. In this study, we jointly inverted the MT and RF data utilizing Pareto-based multiobjective particle swarm optimization (MOPSO) based on a structurally constrained approach without restricting the direction of the model parameters and compared the results with structurally coupled approach. MOPSO, which overcomes the difficulties of traditional inversion such as the dependence on the initial model and the trapping of local minima, achieves a global solution without requiring a regularization operator for either the model parameters or misfit functions. The presented approach was verified on synthetic models and an application from field data obtained from measurements at a single station on the Biga Peninsula in Turkey. The results of these analyses confirm the usefulness of the method as a new approach for joint inversion of geophysical data sensitive to different physical phenomena.

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JS06a - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Multimethod imaging of naturally and anthropologically induced landslide in the Outer Carpathians - result of 4-year observations

DOI: 10.57757/IUGG23-0827 - LINK

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[1]Institute of Geophysics Polish Academy of Sciences, Geophysical Imaging, Warsaw, Poland
[2]University of Warsaw, Faculty of Geology, Warsaw, Poland
[3]Institute of Geophysics Polish Academy of Sciences, Polar Research, Warsaw, Poland
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[6]Mineral and Energy Economy Research Institute Polish Academy of Sciences, The Department of Circular Economy, Kraków, Poland

Landslides represent one of the greatest challenges of modern earth sciences. Vulnerable to external as well as anthropogenic factors, these phenomena require extensive research and monitoring of zones at risk of their occurrence. In this work we present an integrated approach to such phenomena, using the example of a landslide in the Outer Carpathians. In the case described, active seismic methods such as reflection imaging, refraction tomography and surface wave analysis were combined with electrical resistivity and magnetic methods. The entire data set is complemented by a detailed terrain model made using the TLS technique and passive seismological monitoring from 5 temporary broadband stations located around the landslide. The result of 4 years of observations is an accurate image of changes in the landslide zone at very high resolution, with analysis of uncertainty. As a result of the study, it was possible to separate the natural triggers of the landslide, from the anthropogenic ones, as well as to determine the influence of each type on the evolution of the slip zone. The presented research is an important example for problems of much greater strategic importance, where similar effects are to be expected in the results of observed climate changes.

This research was funded by the National Science Centre, Poland (NCN), grant number 2020/37/N/ST10/01486.

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JS06a - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Determining high-resolution lithospheric structure by joint inversion of body wave arrival times, surface wave dispersion data and receiver functions

DOI: 10.57757/IUGG23-1162 - LINK

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Different types of seismic data, including body wave arrival times, surface wave dispersion data and receiver functions, have been widely used to determine the lithosphere structure through seismic traveltime tomography, surface wave tomography and receiver function imaging, respectively. However, different data types have different strengths on resolving the lithospheric structure. For example, seismic traveltime tomography using body wave arrivals only better resolves the structure where ray paths are dense and generally the shallow structure is poorly resolved. Surface wave tomography can determine the shallow structure well if shorter periods of dispersion data are available but generally has poorer model resolution in depth. In comparison, receiver function imaging can resolve the interfaces in depth but is not very sensitive to the absolve velocity changes. Therefore, it is necessary to develop a joint inversion algorithm to combine these different seismic data to better determine the lithospheric structure.

We have developed a new joint inversion method that incorporates body wave arrival times, surface wave dispersion and receiver functions to simultaneously update earthquake locations and constrain three-dimensional P-wave (Vp) and S-wave velocity (Vs) models. Synthetic tests demonstrate the advantages of this new joint inversion algorithm in resolving velocity structures, especially in constraining velocity gradients across the Moho interface. We have applied the new algorithm to different tectonic regions including south China, north China, and southwest China. Combined with geochemical data, we have gained new insights on the lithospheric structure of these regions.

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JS06b - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Geophysical constraints and perspectives for modeling the shape and velocity of a magmatic intrusion at Piton de la Fournaise

DOI: 10.57757/IUGG23-2580 - LINK

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[3]*ISTerre, Volcano geophysics and geothermics, Le Bourget du Lac, France*

Magma is a viscous fluid that can propagate through the crust by fracturing rocks and flowing through them. These magma-filled fractures are called dykes. Magma pressure is the force ensuring the opening of the fracture and maintaining the magma flow. We combine numerical modeling with geophysical data to explore the dynamics of dyke propagation. Although physics-based models provide simplified but reliable representations of dykes, few account for the full interaction between rock fracturing and magma viscous flow. They are limited to planar fracture propagation, and cannot address any change in the direction of propagation of an intrusion. To overcome this challenge, we developed a modeling scheme for the propagation of magmatic dykes by implementing viscous flow equations in an existing 2D boundary element model. Given the crustal stress state, the physical parameters of the crust and magma, and the initial geometry of the fracture, our model allows to jointly estimate the shape, trajectory and velocity of a dyke. Once the results of the model have been validated with analytical solutions, we applied it to the vertical propagation of the 1998 intrusion at Piton de la Fournaise (La Réunion Island). We constrained part of the model parameters with observations and varied the dyke length and the fracture toughness of the rocks, obtaining different propagation velocities, which we compared with the spatio-temporal evolution of volcano-tectonic events recorded before the eruption. Finally, the best-fit solution of this forward method is put into perspective with previous deformation sources resulting from geodetic data inversion.

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JS06b - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Multivariate statistics of geophysical and geochemical data at Teide volcano (Tenerife, Spain)

DOI: 10.57757/IUGG23-2742 - LINK

Luca D'auria[1,2], María Asensio-Ramos[1], José Barrancos[1,2], Iván Cabrera-Pérez[1], Rubén García-Hernández[1], Pedro A. Hernández Pérez[1,2], David Martínez van Dorth[1,2], Gladys V. Melián[1,2], Victor Ortega[1], Germán D. Padilla[1,2], Eleazar Padrón[1,2], Monika Przeor[1,2], Fátima Rodríguez[1], Nemesio M. Pérez[1,2]
[1]Instituto Volcanológico de Canarias INVOLCAN, Vigilancia Volcánica, San Cristóbal de La Laguna, Spain
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The joint analysis of multiparametric datasets in geophysics and, in general, in geosciences is often challenging due to the highly different measurement types. During the last decades, data mining techniques have been subject to intense development, which allows the detection and characterizing of "hidden patterns" within complex datasets.
One of the most successful and widely used techniques is the Independent Component Analysis (ICA) which allows for identifying spatio-temporal patterns related to independent sources from dense geospatial datasets. In this work, we apply an extension of the ICA named Independent Vector Analysis (IVA) to analyze a multiparametric dataset of spontaneous potential, CO_2 and H_2S flux and thermal gradient measurement realized in the crater of Mt. Teide (Tenerife, Canary Islands), from 2020 to 2023. While ICA allows studying spatio-temporal patterns of a single quantity, IVA allows dealing with means multiparametric measurements realized on a single point, which means using vector data instead of a simple scalar.

The relationship between spontaneous potential and gas emission is well known and testified by numerous case studies. In this work, however, we exploit for the first time this quantitative approach to separate and characterize endogenous and external factors in this dataset. The approach we propose in this work has a broader application to repeated multiparametric geophysical surveys and in combining geophysical datasets with other kinds of data.

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JS06b - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Dealing with sparse geophysical data interpretation, limits of gravity inversion

DOI: 10.57757/IUGG23-0094 - LINK

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The paper addresses consequences of an inappropriate geophysical observations' coverage on the quality of data interpretation. For instance, investigation of volcanic areas often faces the problem of data scarcity due to access difficulties. The case study of Ciomadul, the youngest volcano in the Carpathian-Pannonian region has been considered. Previous research, based on sparse MTS data inversion had suggested the presence of a large magma chamber beneath it, at a relatively shallow depth, raising the issue of the volcanic hazard. A subsequent joint gravity and magnetic survey outlined a mass deficit beneath the volcano, overlapping the electrical resistivity anomaly outlined by previous electromagnetic survey and interpreted as an active magma chamber.

Anyway, geological interpretation of the gravity inversion proved to be misleading as long as the suggested model was not supported by results of the geomagnetic inversion and geological constraints. Consequently, limitations of the gravity inversion were subject to basic research. It demonstrated that (quasi) one-dimensional sources such as low-density narrow volcanic conduits (having cross-section size inappropriate to the survey's Nyquist frequency) may be reflected by gravity inversion as three-dimensional mass deficits due to an inappropriate spacing between observations.

Given the shortcomings revealed, gravity data were re-interpreted by jointly employing the inversion results and forward modelling approach, and a new model of the volcano structure has been proposed. It substitutes the formerly assumed magma chamber by a well-developed plumbing system with volcanic conduits of high fluid content, including electrolytes that may also fully justify the geoelectric anomaly previously outlined.

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JS06b - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

The 2021 Tyrnavos earthquake sequence in Greece: complex faulting constrained through a combined analysis of geological, geodetic and seismic data

DOI: 10.57757/IUGG23-2037 - LINK

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In March 2021 an earthquake sequence, including three Mw ~6 normal fault earthquakes on the 3rd, the 4th and the 12th of March, shook Thessaly in central Greece. The epicentres of the three mainshocks propagated northwestward to rupture the northern tip of a large-scale (>100 km) fault relay structure that traverses central Greece. InSAR analysis coupled with field investigations show that only the first and largest earthquake is characterized by a clear rupture that reached the surface along a mapped fault with sharp geomorphic signature. In contrast, the following two large earthquakes were blind, despite the presence of clear pre-existing fault traces near the respective epicentres. Here, we present a kinematic source optimization for which we combine teleseismic waveforms, InSAR and GNSS displacements together with geological constraints to estimate the first-order rupture parameters for location, geometry, slip mechanism and rupture dynamics. This multidisciplinary approach provides a robust source solution, particularly for the first two earthquakes that occurred less than 24 hours apart. The short interval between these events means that with InSAR data the two ruptures were only separately imaged from ascending satellite look direction. In our optimization we consider the individual data errors in data weighting and we perform a fully Bayesian source model uncertainty analysis. Our results reveal the sequential activation of at least 8 individual faults along the relay fault zone, including numerous syn-seismically activated secondary faults. These, together with remapping and analysis of regional faults, reveal the presence of a mature large-scale relay zone.

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JS06b - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Crustal rheology and seismicity in the eastern Central Asian Orogenic Belt and its tectonic implications

DOI: 10.57757/IUGG23-0336 - LINK

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The Central Asian Orogenic Belt (CAOB), located between the Siberia and Baltica cratons to the north, and the Tarim and North China cratons to the south, is a large and long-lived accretionary orogen that extends from the Urals in the west through Kazakhstan, Magnolia, China to the Okhotsk Sea in Russia, with the ocean closing during Neoproterozoic to the Late Phanerozoic. Quaternary volcanoes and earthquakes are widespread in the northeastern China of eastern CAOB, along with high heat flow background, obviously affected by the subduction of the Pacific slab; however, the range and manner of this subduction effects still remain elusive. Seismogenic depths in northeastern China show that, bounded by the Great Xing'an Range, the seismicity in the west is diffusely distributed in the crust, with a bimodal pattern as the upper and middle/lower crust (15-25 km); while for the east area, the seismicity only occurs in the upper crust (~15 km). Rheological modeling demonstrates, only the rheologically weak crust in the east with wet condition and strong crust in the west with dry condition, can reconcile the observed seismicity, suggesting the control of differential crustal rheology. Combing with other geological and geophysical observations, we propose that the stagnation and associated dehydration of the subducted Pacific slab underneath the northeastern China could account for this rheological contrast. Our findings further confirm that the North-South Gravity Lineament in East China, geographically representative of the Great Xing'an Range-Taihang Mountain, as a large-scale tectonic boundary, marks the westward limit of the subduction.

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Range-Taihang Mountain, as a large-scale tectonic boundary, marks the westward limit of the subduction.

JS07a - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Dynamical consequences for dynamo action subject to thermal core-mantle interaction in presence of stably stratified layer

DOI: 10.57757/IUGG23-3180 - LINK

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Stable stratified layer near CMB plays a significant role both on the flow pattern in the outer core, as well as the morphology of the geomagnetic field. Using a radially varying heat source various temperature profiles have been generated. These profiles are characterised based on the presence of a stable stratified layer, of varying thickness, near the outer boundary. The dynamics of the Earth's outer core convection is the central focus of this study. Heat flux variation at the outer boundary, with three different amplitudes of spherical harmonic pattern, is imposed to mimic core-mantle thermal interactions. The flow structures are analysed based on the vorticity dynamics and the role of helical flow structures, responsible for dynamo action and generating magnetic fields. It is observed that although the anticyclonic helicity is dominant over the cyclonic helicity, positive heat flux promotes the cyclonic helicity whereas the negative heat flux promotes the anticyclonic helicity in strongly driven convection. In rapidly rotating regime, thicker stratified layer tries to damp the magnetic field across the layer resulting in a large scale field at the CMB. Finally, it is also seen that high heat flux boundary forcing causes the dynamo action to fail.

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JS07a - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Enhancing mantle downwellings through gravitational collapse of a metal-silicate mushy layer at the core-mantle boundary: implications on core-mantle interactions

DOI: 10.57757/IUGG23-1954 - LINK

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The core-mantle boundary (CMB) is one of the most stable interfaces inside the Earth due to the large density and viscosity contrasts. Despite significant differences in physical, chemical, and transport properties, the possible mechanisms where the core and mantle can interact has become an active area of research. Detection of chemical signatures from the CMB can provide an unprecedented glimpse into the Earth's deep interior and ancient past, with some studies suggesting certain isotopic and elemental anomalies in ocean island basalts to be core tracers. However, there is still uncertainty regarding processes that can convey chemical signatures from the core to the mantle. A recent study proposed a new hybrid mechanism that results from collaborative feedback between dynamic topography, percolation of liquid metal into submerged rock, the gravitational collapse of a metal-silicate mush, and induced small-scale mantle circulation above this mushy layer. The grain-scale intrusion of liquid iron into mantle rocks offers an opportunity for chemical and isotopic exchange to take place, while the gravitational collapse of the mushy layer can "soften" the CMB and enhance downwellings, thereby encouraging further chemical exchange. Using a mantle convection model coupled to the gravitational spreading of a thin layer at the CMB, we will show how the enhancement of downwellings change with the rheology of the mantle, and if the reacted mantle materials emerge from the mushy layer with a certain buoyancy ratio, how much of it will be entrained in upwelling plumes.

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JS07a - Geophysical Constraints on the Earth’s Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Magnetic boundary layers in numerical dynamos with heterogeneous outer boundary heat flux

DOI: 10.57757/IUGG23-1571 - [LINK]

Filipe Terra-Nova[1], *Hagay Amit*[1]
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It has been proposed that magnetic flux expulsion due to outer core fluid upwellings may affect the geomagnetic secular variation on the core-mantle boundary (Bloxham, 1986). In this process intense horizontal field lines are concentrated below the outer boundary, introducing small radial length scales and consequently strong radial diffusion. We explore such magnetic boundary layers in numerical dynamo simulations with heterogeneous outer boundary heat flux inferred from a tomographic model of lower mantle seismic shear waves velocity anomalies. Our scheme associates magnetic boundary layers to peak horizontal magnetic fields at the top of the shell. In our models mean magnetic boundary layer thickness ranges ≈200-400 km and decreases with increasing magnetic Reynolds number. Extrapolation or interpolation to Earth's core conditions based on total core flow amplitude or its poloidal part gives mean magnetic boundary layer thickness of ≈220 and ≈260-330 km, respectively. We find magnetic boundary layers associated with the azimuthal field at the equatorial region, whereas magnetic boundary layers associated with the meridional field are found at mid latitudes. Negative outer boundary heat flux anomalies yield preferred locations of expulsion of azimuthal field below Africa and the Pacific (at low latitudes of the Northern Hemisphere.), while positive outer boundary heat flux anomalies yield preferred locations of expulsion of meridional field below the Americas and East Asia. Our results suggest that the local diffusion time is on the order of several kyr and the local magnetic Reynolds number is on the order of ≈10, both much smaller than classical estimates.

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JS07a - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Precession-driven flows and turbulence in planetary liquid cores

DOI: 10.57757/IUGG23-0849 - [LINK]

Jeremie Vidal[1], *David Cébron*[1]
[1]*CNRS - Université Grenoble Alpes, ISTerre, Grenoble, France*

The deep interior of planets can be indirectly investigated using rotational motions such as precession or nutations. Turbulent flows driven by precession have also been proposed for generating dynamo in planetary cores (e.g. to explain the early Earth or Moon's paleofield). In the frame of the ERC THEIA, we focus on bulk turbulent flows that are promising for planetary applications (since they are driven by topographic effects instead of viscosity). To probe the low-viscosity regime of planetary interiors, we investigate precession-driven flows in stress-free ellipsoids using asymptotic analysis and simulations. Contrary to previous expectations, we show that this model could unlock numerical difficulties of no-slip simulations. In a regime relevant to planets, we obtain the flow forced in triaxial cores, exhibiting a second mode resonance. Then, we investigate the transition towards turbulence through the bulk instabilities driven by precession in ellipsoids (the conical-shear instability and the inertial instabilities). We also provide scaling laws for the saturation amplitude of these instabilities, which are relevant for planetary applications but often hampered in experiments or no-slip simulations. Then, we study the dynamo capability of these flows for the Earth and Moon over geological times. Finally, we outline that precession could interact nonlinearly with the nutations, which might be key to interpret the dissipation at the core-mantle boundary observed in the nutation data.

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JS07a - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Topographic coupling in the outermost stratified layer of the Earth's core

DOI: 10.57757/IUGG23-0848 - LINK

Rémy Monville[1]*, David Cébron*[1]*, Dominique Jault*[1]
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The accurate tracking of the Earth's rotation allows us to constrain the coupling between the liquid core and the mantle. However, despite well-constrained values, the coupling mechanisms are still disputed. These couplings are not straightforward to calculate and can originate from pressure, gravity, viscous, or electromagnetic forces. Studies have therefore studied whether these observations can be due to the laminar dynamics of a stratified fluid layer, below a bumpy Core-Mantle boundary (CMB). Investigating the stress generated by the flows in this thin layer, they concluded that they could explain the observed Earth length-of-day variations (Jault, 2020; Glane, 2018) or the dissipation of the annual nutation (Buffett, 2010). However, these conclusions rely on leading order perturbative calculations, sometimes applied beyond their range of validity e.g. by using too high topographies, in addition to having been performed under multiple assumptions. Our code, based on plane-wave perturbations in a local reference frame, allows us to estimate the torque at the CMB using mixed high-precision symbolic calculations. We calculate "higher-order" solutions that go beyond the forced-wave linear regime. This new method explores a wide range of parameters and boundary conditions for arbitrary topography shapes. We also consider the spherical geometry via spatial integration, which includes the lateral variations of the magnetic field and the rotation vector's orientation.
Funded by ERC THEIA (grant agreement no.847433)

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JS07a - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Onset of convection in a rotating plane fluid layer subject to non-uniform boundary heating and stable thermal gradients

DOI: 10.57757/IUGG23-1783 - LINK

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The instabilities that arise in a rotating plane layer due to imposed vertical temperature form the basis of fluid flow structures in outer Earth's core. The temperature profile in the Earth's outer core, being affected by various conditions such as secular cooling, bottom heating at the inner core surface, is believed to be modulated by thermal conditions near the core-mantle boundary. The present study investigated the role of such modulations by imposing a layer of stably stratified fluid near the top boundary and imposing a sinusoidal temperature variations over and above the reference case of isothermal condition used in the classical Rayleigh–Benard convection. Such conditions result in the top–bottom flow asymmetry that cause flow localization and changed temporal dynamics compared to the classical Rayleigh–Benard cells. The minimum buoyancy forcing required for convection is also lowered with flows in surplus heat flux regions. The flow suppression in the stable layer is overcome by the effects of rapid rotation enhancing the penetration of convection columns with smaller length scales. The heterogeneous temperature conditions imposed at the top boundary also cause axially penetrative convection instabilities unlike the reference case. The onset of oscillatory convection modes is dominant in low Prandtl number cases, which is relevant to the Earth's core conditions. The dominance of Coriolis force for rapid rotation cases causes a traveling wave instability, the propagation direction of which is determined by the heat flux occurring at the top boundary.

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JS07b - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

GRACE/SLR-based gravity field and the Earth's core: New estimates for parameters of key core processes

DOI: 10.57757/IUGG23-0184 - [LINK]

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[3]University of Alberta, Department of Physics, Edmonton, Canada

The Earth's interior, particularly the Earth's fluid outer core, possesses a broad dynamics of processes involving mass variations. Theoretical models predict variations of the gravity field at low degrees and at inter-annual / decadal time scales. These include dynamic pressure changes at the Core Mantle Boundary (CMB) associated with core flows reconstructed from geomagnetic observations and reorientation of the inner core controlled by gravitational coupling with the mantle. The hypothetical effects due to some dissolution/crystallization at the CMB introduce a time-varying roughness of the interface. Taking into account these considerations, for the first time, we investigate the density and pressure changes obtained from magneto-hydro-dynamics (MHD) simulations that reproduce geomagnetic jerks.

Besides the geomagnetic information, we also are interested in exploiting long series of gravity measurements. The time-variable Earth's gravity field is measured by satellite missions such as GRACE and GRACE Follow-On and by Satellite Laser Ranging (SLR). These products enable to study continental hydrology, oceanic and atmospheric loading, post-glacial rebound, glaciers, earthquakes and other phenomena that involve mass variations. The comparison of GRACE and SLR gravity field variations with Earth's core predicted signals gives new inputs on parameters of the Earth's core processes. This study provides new upper-bound values for pressure anomalies at the CMB and angle of reorientation for the inner core.

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JS07b - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Separation of core and lithospheric signals in satellite magnetic data

DOI: 10.57757/IUGG23-2850 - LINK

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Satellite observations of the geomagnetic field contain signals that originate both from electrical currents in the core and from magnetized material in the lithosphere. At short wavelengths the lithospheric signal dominates, obscuring the signal from the core. The standard procedure is to simply take the internal field up to spherical harmonic degree 13 to be the core field. Here we demonstrate that separate models of the core and lithospheric fields, overlapping in spherical harmonic degree, can be co-estimated provided one makes use of relevant prior information on the sources. Using a maximum entropy modelling approach, we find models for the time-dependent core field and static lithospheric field that satisfy the constraints provided by satellite observations, as well as statistical prior information on the sources (the expected variance and correlation functions for the radial field), but are otherwise maximally non-committal with regard to the distribution of radial magnetic field at the source surfaces. Tests using synthetic data are encouraging, indicating that using our approach it is possible to retrieve parts of the core field beyond degree 13 and the lithospheric field below degree 13. Results for the time-dependent field at the core surface up to spherical harmonic degree 30 will be presented and implications for our understanding of the core dynamo, in particular its high latitude flux patches, the field structure inside the tangent cylinder, and the nature of westward drifting field concentrations at low latitudes, will be discussed.

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JS07b - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

The 8.4 year oscillation as an excitation method: Using spline derivatives for probing signals in the length-of-day record.

DOI: 10.57757/IUGG23-1559 - [LINK]

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Intradecadal variations in the length-of-day (ΔLOD), once corrected for atmospheric effects, can reveal changes in angular velocity interpreted as due to Earth's core. Previous studies have identified periodic oscillations of around 6 and 8 years (6YO and 8YO, respectively). To complement widely used Fourier methods, we investigate the ΔLOD record from 1962—2023 in the time domain, seeking smooth variations using cubic splines.

We analyse in several ways. A smooth (but not band limited) curve fit with least-squares splines allows removal of the long-term behaviour of ΔLOD. We then fit the residual with a pure cosine-wave of varying period but examine the data fits carefully in case the signal is non-stationary (for example from impulsive forcing). Alternatively, a penalised least-squares spline fit allows isolation of coherent variations from analysing the first and second derivatives.

All approaches show clear evidence of signals with periods around 6 and 8 years. Earlier work (Holme and de Viron 2013) focussed on a 5.88 year variation for the period in 1962—2010, although, this appeared to break down, with the next extremum following in only 4 years. However, the next maximum has appeared in 2021, consistent overall with an approximate 6 year variation. We explain this from periodic discontinuities in the 6YO with an ~8 year period, providing a new explanation for the nature of the 8YO as an episodic rather than harmonic signal. Given that frequency-domain based methods do not treat discontinuous signals, this feature will be lost using Fourier theory.

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JS07b - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Using SOLA for investigating regional dynamics of flow at the top of the outer core

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Investigating the dynamics of liquid iron at the top of the core requires an inversion process from magnetic field measurements. Due to possible leakage, traditional spectral techniques are not optimal for regional investigations or studies of Secular Variation (first time derivative of magnetic field, SV) on short-time periods. Improved data coverage and quality from satellite missions have provided insight into short-period dynamics (such as jerks and waves), and improved understanding of localised features. However, there continues to be a need for new techniques for better spatio-temporal models of flow motions at the top of the core, especially for regional investigations.

The aim of this work is to investigate regional dynamics at the Core-Mantle Boundary (CMB) using the SOLA (Subtractive Optimally Localised Averages) methodology. This method allows us to create point estimates of radial field SV at the CMB by considering global satellite measurements. The SOLA methodology allows for a local estimate of radial field SV at any desired location directly at the CMB, which opens the way to investigations of regional dynamics. Producing localised-average estimates at the CMB bypasses many problems encountered when using only a subset of magnetic satellite data, downward continuing data, and models based on spherical harmonics.

Finally, we discuss how the SOLA methodology can be incorporated into the PyGeodyn code to produce core flow models. This approach can provide additional information on wave-like flow motions at the top of the Earth's core where these are most prominent, and permits new investigations of shorter period phenomenon.

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JS07b - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Estimating common signals of the spatial gravity and geomagnetic field related to the Earth's core field variation

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Our knowledge of the Earth's liquid core dynamics is based on indirect information sources. One of the crucial information comes from the geomagnetic field observations, which can be used to infer variations of the fluid motion at the top of the core. The dynamic of the fluid core is associated with redistributions of the internal mass, which feature density heterogeneities, and the exchange of angular momentum with the solid Earth. Consequently, these processes occurring in the core can produce signatures in the gravitational field. Previous studies indicate that the leading mode of the global temporal gravity variations can be correlated with the leading mode of secular acceleration of the radial geomagnetic field. In this study, by applying several statistical Blind Source Separation (BSS) methods, we investigate the common space-time variabilities that emerge in the geomagnetic and gravity fields. Oscillations around 6-7 years are present in most of the analyses of both fields. The common areas where both magnetic and gravity field exhibit such variations include the South-Pacific Ocean, the northern part of Africa, and India. We note that 6-7 year oscillation in the geomagnetic field has also been reported in some previous studies as a mode attributed to the Quasi-Geostrophic (QG), Magneto-Coriolis (MC) and Alfvén waves in the liquid core. The possible causes for such oscillations in the gravity field are still under investigation.

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JS07c - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Length-of-day, geostrophic motions in the core, and the conductance of the mantle

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Numerical simulations of the geodynamo are used to investigate the transfer of angular momentum between the core and the mantle, in the presence of both an electro-magnetic torque and a gravitational torque between the inner core and the mantle. Over a broad range of periods, angular momentum changes are accurately explained when deriving geostrophic motions (organized as cylinders co-axial with the Earth's rotation vector) from core surface motions. Inverted core surface flows can thus be used to infer the core angular momentum budget. In the dynamo, the largest part of the EM torque variations is associated with the evolution of the solid body rotation, with little contribution from electrical currents originating deep inside the core (the "leakage torque", formerly associated with the westward drift of the geomagnetic field). A 1D model of geostrophic motions is furthermore used to estimate the efficiency of torsional eigenmodes to couple with the solid Earth. From this we revisit the estimate of the mantle conductance from 1D simulations of geostrophic motions stochastically forced in the volume. We then discuss the ability of torsional waves to trigger the interannual oscillations observed in the length-of-day series, and the relative importance of forcing versus resonances in angular momentum changes at various time-scales.

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JS07c - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Sensitivity of Swarm magnetic data to lateral variations of the electrical conductivity in the lower mantle

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The large-scale electrical conductivity structures in the deep Earth's mantle can be in principle determined from Swarm-observed induction response to time-variable magnetospheric currents. Here we present a new sensitivity study based on the 3-D time-domain modelling of the electromagnetic induction in the Earth's mantle, aimed at the lowermost mantle. So far, these efforts have been encumbered by limited spatio-temporal description of the magnetospheric field from moving satellite platforms. In particular, the polar electrojets (PEJs) and field-aligned currents (FACs) are sources of a strong bias in the spherical-harmonic analysis of Swarm magnetic data. Our approach exploits the recently introduced improvements to the processing of Swarm magnetic data. An electric circuit model of PEJs and FACs provides a novel data processing tool to suppress the bias and provide a reliable model of the large-scale magnetospheric field during magnetically disturbed times. In this contribution we determine the sensitivity and resolution of the inverse problem, and proceed with regularized 1-D and 3-D inversions to update the electrical conductivity model of the lower mantle.

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JS07c - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Intradecadal variations in length of day: Coherence with Earth's core flow models

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The variations of the Earth's length of day (LOD) exhibit several interannual oscillations. The first detected one, with a period of 5.9-year, is better seen after removing the atmospheric contribution. More recently was isolated an oscillation of period ~8.5-year, distinct from the previous one. Torsional waves could explain both signals, although recently discovered non-axisymmetric magneto-Coriolis waves may also be involved. With a much smaller amplitude, a 7.3-year fluctuation was also detected in LOD data but no physical mechanism has been proposed. We show using a continuous wavelet transform analysis of synthetic oscillators embedded into a random noise, the limits of isolating damped signals with nearby periods in time series of limited duration. In particular, we emphasize the possibility that the 7.3-year oscillation could originate from an artifact due to the restricted length of the LOD series. Finally, we perform a wavelet coherence analysis between geodetically observed LOD variations and predicted LOD changes from geomagnetically inferred core flow models. Observed coherence at 5.9-year and ~8.5-year periods most probably confirms the fluid outer core origin for these two oscillations. Two coherent oscillations around 3.5 and 5-year periods are also conspicuous. Torsional Alfvén waves and/or Quasi-geostrophic magneto-Coriolis waves are natural explanations to the presence of various quasi-periodic signals in the LOD at interannual time-scales.

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Core surface flow inversion using physics-informed neural networks and dynamic mode decomposition of the core flow

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In this study, we use physics-informed neural networks to inverse the core surface flow from the geomagnetic observations. We start from the radial component of the induction equation under the frozen-flux approximation and tangentially geostrophic flows assumption. We retrieve the core surface flow field between 2000 and 2020 using the core magnetic field model CHAOS-7. We then perform the dynamic mode decomposition for the retrieved core flow. This method decomposes the flow field and SV into several eigenmodes with time evolution. The consistency time evolution between the flow and the SV modes indicates the inversion algorithm is stable. Moreover, we calculate the secular acceleration (SA) of the magnetic field for each dynamic modes and find the mode with a period of about 8 years can match the jerk events occurred in the equatorial region.

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JS07c - Geophysical Constraints on the Earth’s Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Hydromagnetic Waves in the Equatorial Region: Analysis Using Dynamic Mode Decomposition and Complex Empirical Orthogonal Functions

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Short-period fluctuations in the Earth's geomagnetic field have been observed through satellite observations over the past 20 years. Our previous study (Chi-Durán et al., 2020) found evidence of eastward and westward traveling waves with periods of 7.08 ± 0.58 and 15.73 ± 4.44 years, respectively, in the Atlantic and South Asia regions. These estimates were obtained by applying complex empirical orthogonal functions (CEOFs) to the geomagnetic secular acceleration from localized regions of the CHAOS6 model (Finlay et al., 2016). More recently, we have applied dynamic mode decomposition (DMD) to investigate the temporal evolution of the radial magnetic field (Br) and secular variation (SV) at high latitudes using CHAOS7 (Finlay et al., 2020). In this study, we extend the DMD analysis to the entire equatorial region using Br and SV. We discover traveling waves with propagation directions and periods close to those detected using COEFs. The consistency of the two results points to a common underlying dynamics in the CHAOS models. An unexpected advantage of the DMD method is that it can recover localized dynamics, even when applied to a much broader region (i.e. the entire equatorial region). These findings emphasize the potential of DMD as a tool for identifying traveling magnetic waves in the core and provide an additional understanding of CEOFs. These results are significant for comprehending the dynamics of the geomagnetic field and its impact on the Earth's outer core structure.

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JS08a - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

New heat flow measurements in the Alboran Sea, westernmost Mediterranean Sea

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15 new heat flow measurements were obtained during the ALBACORE cruise (R/V Pourquoi Pas ?) in 2021 in the Alboran Sea, the westernmost part of the Mediterranean Sea. Temperature gradients were measured using autonomous thermal probes attached to sediment corers with a length of 6 meters. Thermal conductivity was measured onboard using a needle probe instrument on recovered sediment cores. In previous studies, a large difference in heat flow has been observed between the western and eastern parts of the Alboran Basin, 69 ± 6 mWm^{-2} versus 124 ± 8 mWm^{-2}. Here we focus on the mainly North-South Bokkoya and Al Idrissi active strike-slip fault zones between these two domains. Three heat flow profiles were performed perpendicular to the fault zones that show a marked difference in heat flow values along and between these profiles. The northern profile, 2.5 km long, indicates a homogeneous heat flow with a mean value of 65 mWm^{-2}. The middle profile shows a heterogeneous heat flow with a mean of 81 mWm^{-2} and variations of ± 30 mWm^{-2} over a 400 m distance. The southern profile indicates high and heterogeneous heat flow values varying between 155 and 204 mWm^{-2} over the 550 m long profile. These local thermal anomalies could be associated with hydrothermal activity along the fault segments. Transport of heat by hydrothermal circulation has been observed in different geological settings. In the Alboran sea basin, some segments of the active fault zones may thus display suitable pathway for hydrothermal circulation.

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JS08a - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow density measurements in offshore continental crust

DOI: 10.57757/IUGG23-3382 - LINK

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The heat flow in offshore sedimentary basins may be measured using techniques developed for marine domain or using data acquired in wells drilled in oil/gas prospecting works. Sometimes the depth reached in these wells may be very different in relatively close wells. In the deepest wells heat flow variations with depth can be studied and the differences in heat flow values at the surface may be explained.

The problem is ilustrated using a real exemple with heat flow density values obtained in a region located in the Southern border of the Eurasion plate in three wells, located at similar latitudes, drilled for oil/gas prospecting works. The region has been studied by several teams trying to obtain a tectonic model, without sucess until now.

The heat flow density values obtained in two of the wells are similar but in the third well, the deepest one, the heat flow value is the highest. Gamma-ray,density and porosity logs were used to obtain information about heat sources and thermal conductivity values in depth. The results obtained in the third well show an increase of heat flow with depth, possibly related with turbidity currents in the region and horizontal movement of matter (water and sediments) and heat release by advection.

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JS08a - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow and thermal structure of the South China Sea

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As the biggest marginal sea in western Pacific region, the South China Sea (SCS) has attracted increasing attention owing to its resource potential and environmental capacity. However, the origin and opening process of the SCS remains elusive. Thermal imprints could provide clues for regional tectonics. This paper aims to decipher the thermal state of the SCS integrating the IHFC heat flow dataset with new measurements (a total of 902 measurements). Results show the SCS has an average heat flow of 75 mW/m^2, and nearly 80% of the heat flow values range between 50-100 mW/m^2, indicative of a hot basin in geothermal characterization. Heat flow pattern of the SCS shows remarkable lateral variations in different tectonic units. Among which, the Central Oceanic Basin exhibits the highest heat flow, and the average values of the northwest sub-basin, the southwest sub-basin and the eastern sub-basin are 98 mW/m^2, 99 mW/m^2 and 91 mW/m^2, respectively. Both the western margin and southwestern continental margins are characterized by generally high heat flow accompanied with large faults. The heat flow in the northern margin increases from the continental shelf to the slope, as a result of differential crustal extension. In contrast, the eastern margin is quite cold, owing to the subduction induced cooling effect. The thermal structure shows that heat flow from mantle is dominative in observed seafloor heat flow. Besides, local heat flow anomalies within the SCS can be attributed to hydrothermal circulation, magmatic activities and sediment thermal effects.

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JS08a - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow and thermal regime in the Guaymas basin, gulf of California: Estimates of conductive and advective heat transport

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[4]*University of Bremen, Department of Geosciences- Section Petrology of the Ocean Crust, Bremen, Germany*
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Heat flow is reported at eight sites drilled into the Guaymas Basin, Gulf of California, during the International Ocean Discovery Program Expedition 385. This expedition seeks to understand the thermal regime of the basin and heat transfer between off-axis sills intruding the organic-rich sediments of the Guaymas Basin, and the basin floor. The relatively high sedimentation rates combined with active tectonism and voluminous shallow off-axis magmatism characterizes this basin. Our results bridge a data deficiency allowing basin-wide interpretations shading light on this young rift basin. Results show sedimentation corrected heat flow values range between 119 and 221 mW/m^2 in the basin and between 257 and 1003 mW/m^2 at the site of a young sill intrusion, termed Ringvent. Thermal analysis shows that heat in the Guaymas Basin is being dissipated by conduction for plate ages >0.2 Ma, whereas younger plate ages are also dissipating heat by advection. Drilling data show that an active ring of hydrothermal vent root to a shallow sill fueling low-temperature hydrothermal fluids with discharge velocities of 10–200 mm/yr. Possible recharge sites are located ~1 km away from the sill's border. Modeling of the heat output and assuming supplied by a cooling sill, we estimate a sill thickness at Ringvent of ~240 m. A simple order-of-magnitude model predicts that relatively small amounts of magma are needed to account for the elevated heat flow in non-volcanic, sediment-filled rifts like the central and northern Gulf of California where heating of the upper crust is achieved via advection by sill emplacement and hydrothermal circulation. Multiple timescales of cooling control the crustal, chemical and biological evolution of the Guaymas Basin. Here we recognize at least four timescales: the time interval between intrusions (~10^3 yr), the thermal relaxation time of sills (~10^4 yr), the characteristic warming time of the sediments (~10^5 yr), and the cooling of the entire crust at geologic timescales.

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JS08a - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat transport by hydrothermal circulation in a young rift: Observations from vent fields in the Pescadero Basin, Gulf of California

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Heat flow measurements collected throughout the Auka and JaichMaa ja' ag' hydrothermal vent fields in the central graben of the Southern Pescadero Basin, southern Gulf of California, indicate upflow of hydrothermal fluids associated with rifting dissipate heat in excess of 10 W/m^2 around faults that have a few kilometers in length. Paradoxically, longer faults do not show signs of venting. Heat flow anomalies slowly decay to background values of ~2 W/m^2 at distances of ~1 km from these faults following an inverse square-root distance law. We develop a near-fault model of heat transport in steady state for the Auka vent field based on the fundamental Green's function solution of the heat equation. The model includes the effects of circulation in fracture networks, and the lateral seepage of geothermal brines to surrounding hemipelagic sediments. We use an optimal fitting method to estimate the reservoir depth, permeability, and circulation rate. Independently derived constraints for the model, indicate the heat source is at a depth of ~5.7 km; from the model, permeability and flow rates in the fracture system are ~10^{-14} m^2 and 10^{-6} m/s, respectively, and ~10^{-16} m^2 and 10^{-8} m/s in the basin aquitards, respectively. Model results point to the importance of fault scaling laws in controlling sediment-hosted vent fields and slow circulation throughout low permeability sediments in controlling the brine's chemistry. Although the fault model seems appropriate and straightforward for the Pescadero vents, it does seem to be the exception to the other known sediment-hosted vent fields in the Pacific.

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JS08a - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow measurements and multiphysical integration studies in Campos basin, southeast Brazil

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A large part of the recent oil discoveries in the world is linked to the Brazilian Pre-Salt, and part of the mapped giant/supergiant reservoirs are found in the Campos basin at the Brazilian eastern continental margin. The onshore part of this basin is bordered by the Ribeira Orogenic Belt (ROB), which represents a NE–SW trending system controlled by sliding shear belts, reactivated during its evolution since the Paleoproterozoic. Crustal thermal models have been developed to examine the implications of the observed intracratonic variations on heat flow and thus build an understanding of the geodynamic parameters of basin formation. The geothermal database used in this modeling includes direct and indirect measurements, and was expanded with over 56 locations, providing a spatial extent of 0.5 x 0.5 degrees in the continental part of the basin. The thermal model took into account the variation of thermal conductivity with temperature, as well as the variation of radiogenic heat generation with depth. Results show high values for the heat flow (>70mW/m^2) in the region of the Quadrilátero Ferrífero in the southern part of São Francisco Craton, surrounded by moderate heat flow pattern but increasing significantly in offshore regions where the crustal thickness is much smaller (aprox. 25km). Results of the crustal thermal model integrated with multiphysics (gravity, magnetic and seismic) datasets generate tools for imaging deep structures, especially in the distal portion of the Campos Basin, and map potential basement paleo highs and intrusive magmatic/volcanic features possibly associated to hydrocarbon and geothermal prospects.

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JS08b - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Deep thermal structure in different plate tectonic settings

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The Wilson Cycle describes how plates break apart to form new lithosphere and collide to form orogens. The different stages of this cycle from continetal rifting to passive margin formation and oceanic spreading followed by subduction of oceanic lithosphere until continents collide again creates specific lithospheric configurations characterized by a distinct geophysical fingerprint. Using data-integrated models of orogens and their foreland basins, of rifts and passive margins as well as transform faults we assessed the first-order controlling factors of the related 3D thermal fields. We find that the superposed effects of different thermal conductivities, variable contributions of radiogenic heat in response to crustal thickness and composition, and variations in the average geothermal gradient in response to the thermal thickness of the lithosphere together create setting-specific 3D thermal fields controlling the local rheological configuration and thus deformation. In all settings this basic thermal fingerprint is additionally influenced by moving fluids in the shallow, permeable part of the crust. We show how understanding deformation and finding the geothermal “sweet spots” can profit if the specific local pattern can quantitatively be described.

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JS08b - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat Flow Constraints on Crustal Deformation and Earthquake Activity at the Mendocino Triple Junction, Northern San Andreas Plate Boundary USA

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Heat flow data collected along the San Andreas plate boundary and in the subduction to translation transition at the Mendocino Triple Junction (MTJ) have played a defining role for the geodynamic processes associated with this fundamental change in plate boundary tectonics. In the 1980s, heat flow data led to the recognition that the frictional strength of the San Andreas fault is low (Lachenbruch and Sass, 1980), and there is a slab window in the wake of MTJ migration (Zandt and Furlong, 1982). More recently, heat flow data constrain crustal deformation along the San Andreas corridor (Mendocino Crustal Conveyor; Furlong and Govers, 1999; Guzofski and Furlong, 2002; and Furlong and Schwartz , 2004). These results explain the magnitude and spatial wavelength of the transition from low heat flow within the Cascadia subduction zone to elevated heat flow along the San Andreas plate boundary. Within this broad low-to-high heat flow pattern, there are locations of anomalous heat flow that remain enigmatic. In the region straddling the MTJ, observed heat flow values (75 mW/m2) are substantially higher than are seen both north and south of that region (~ 35 - 50 mW/m2). Combining these heat flow data with new crustal and upper-mantle seismic tomography and tectono-thermal modeling, we constrain the processes of MTJ-related crustal deformation and place the elevated seismicity in the vicinity of the MTJ into its seismo-tectonic context. The elevated heat flow is most likely a consequence of rapid exhumation following the passage of the southern edge of the subducting slab.

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JS08b - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Lithospheric thermal constraints from thermal data and indirect proxies

DOI: 10.57757/IUGG23-2865 - LINK

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Heat flow data is the fundamental parameter in thermal lithospheric studies, which greatly influences tectonic and geological processes. The International Heat Flow Commission (IHFC) has been supporting the compilation of global heat flow data since 1963, and renewed data structure and database is released in 2021 (Fuchs et al., 2021a, b). Besides heat flow data, geothermal gradient and thermal conductivity data may also be useful. However, these data distributions have remained highly uneven, and the data are sometimes uncertain and are likely spatially variable. Therefore, to provide more reliable lithospheric thermal constraints, other proxies based on the complementary interpretation of different geophysical data sets are used. One of the promising proxies is the cut-off depth of crustal seismicity since it has been attributed primarily to the temperature. Another derivative method for constraining lithospheric thermal structure is the depth of magnetic sources based on spectrum analysis of magnetic anomaly data, although this analysis is still controversial. Good inverse correlation between the cut-off depth and heat flow and good correlation between estimated depths of crustal magnetic sources and heat flow suggest that these proxies may reflect the broad average temperature. We discuss the advantages and limitations of each data and method.

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JS08b - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Modeling the Iberian thermal lithosphere. Geodynamic implications and perspectives on deep geothermal studies

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Renewable energy sources are crucial for achieving a transition to a cleaner energy system. Geothermal energy, in particular, is a promising source of energy production. However, its effectiveness depends on a thorough understanding of temperature distribution, fluid circulation, and lithological and petrophysical properties of the crust. Over the past two decades, several methodologies and numerical codes have been developed to better understand the properties of the thermal lithosphere, including its temperature, density, and composition. In this presentation, we summarize the major advances in these developments and discuss their geodynamic implications in the Iberian Peninsula and surrounding regions. Based on available thermal modelling results, we present a compilation of the temperature distribution at different depths in the Iberian Peninsula and the thermal Lithosphere-Asthenosphere Boundary. At a depth of 5 km, temperatures exceed 110°C, with higher local anomalies in the Iberian Massif and Cenozoic volcanic provinces. Similar patterns are observed at depths of 10 and 20 km, with temperatures exceeding 190°C and 350°C, respectively. Although no lithospheric anomalies are observed that could produce high temperatures at shallow depths, there is significant potential for exploitation at intermediate depths. Overall, the potential for direct use of geothermal energy for district and greenhouse heating, as well as for industrial processes, is significant throughout the Peninsula. The main challenges in exploiting this potential are the availability of groundwater and the cost of drilling.

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JS08b - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow, thermal structural and its tectonic implication of the south-central section of the Tan Lu Fault Zone

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Whether active fractures are thermal anomalies is a cutting-edge scientific issue in geothermics. Geothermal measurements of the San Andreas Fault reveal no heat flow anomaly, and then the "heat flow paradox" was proposed. The Tan Lu Fault Zone (TLFZ) is the most important fault in eastern Asia and is still active currently. We have carried out extensive geothermal measurements in the south-central TLFZ: the heat flow in the southern TLFZ is concentrated in the range 55-65 mW/m^2; the highest heat flow site LZSD (93 mW/m^2) is determined by the high heat production rocks, so the southern TLFZ is not a thermal anomaly. In contrast, the heat flow value in the middle section of the TLFZ is over 80 mW/m^2, which is likely to be a thermal anomaly zone. Simulations and calculations show that the heat generated by the fault activity is not significant (1-6 mW/m^2). Detailed two-dimensional temperature field simulation work also confirms these conclusions. The differences in the present-day thermal state of the TLFZ are the result of differences in the influence of tectono-thermal events in different regions, with the "Craton destruction event" at the late Early Cretaceous having altered the property of lithosphere in East China (Lower Yangtze Craton and the north part of the eastern North China Craton), while the south part of the eastern has only undergone the lithospheric thinning process. The difference in paleo-lithosphere thickness is likely the main reason for the different thermal state of the TLFZ.

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JS08b - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Upscaling knoweldge of Antarctic subglacial geothermal heat flux heterogeneity from continental to regional scale

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Geothermal heat flux (GHF) is a critical boundary condition that influences subglacial hydrology and the fast flow of the Antarctic ice sheet and is related to crustal and lithospheric architecture and composition. Despite its importance, Antarctic GHF heterogeneity remains poorly constrained and this hinders broader efforts to study solid earth influences on subice hydrology and ice sheet behaviour.

Within the 4D Antarctica ESA project we produced a new continent-wide aeromagnetic anomaly compilation, conformed at longer wavelengths with SWARM satellite magnetic data and then applied Curie Depth Point (CDP) estimation approaches to provide new estimates of regional-scale GHF heterogenity beneath the West and East Antarctic ice sheets.

Enhanced GHF is revealed beneath the most rapidly changing part of the West Antarctic Ice Sheet along the coast of the Amundsen Sea Embayment. It is inferred to arise from dynamic interactions between the West Antarctic Rift System and anomalously warm Pacific upper mantle underlying the thinned rifted lithosphere. Potential thermal anomalies are also detected beneath the Byrd Subglacial Basin between Thwaites and Pine Island glaciers, and several linear belts of enhanced GHF underlie the Siple Coast ice streams and associated active subglacial lake districts. In East Antarctica, intriguing regions of enhanced GHF are unveiled beneath the Dome C and Dome F lake districts. These may reflect either cryptic intraplate Mesozoic to Cenozoic fault reactivation and/or elevated intracrustal heat production in the inferred Proterozoic crust. Our CDP estimates provide further boundary conditions for the development of next-generation thermal models required to constrain regional GHF heterogeneity.

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JS08c - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow determination in the ICDP COSC-1 borehole and geodynamical implications

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The scientific drilling project "Collisional Orogeny in the Scandinavian Caledonides" (COSC) involved the drilling of two vertical boreholes through the Paleozoic Caledonian orogen in Central Sweden. The present contribution focuses on heat flow determination and evaluates the likely paleothermal state of the lithosphere of Baltica at the onset of the Caledonian orogeny. We concentrated on the results obtained from COSC-1, which was drilled, fully cored and repeatedly logged for temperature down to ~2.5 km depth. Average heat generation of the penetrated Caledonian metamorphic rocks was derived from the spectral gamma ray logs. The analysis yields a low average value of 0.8 μW/m^3. Thermal conductivities were determined from 105 core samples. On average, thermal conductivity equals 2.8±0.4 W/(m K), down to ~2 km depth, and increases to 4.1±1 W/(m K) in the lowermost section of the borehole. The thermal gradient shows obvious paleoclimatic disturbances but seems largely unaffected below ~2 km depth and no advective signal is detected. The calculated heat flow for the deepest section of the well amounts to ~82 mW/m^2. This unusually high heat flow value for cratonic lithosphere reflects, most likely, dominant input from the underlying highly radioactive Transscandinavian Igneous Belt (TIB), which is Late Proterozoic in age. We therefore propose that the lithosphere of Baltica involving the TIB was relatively warm at the time of the Caledonian orogeny. We anticipate that the relatively high temperatures of the margin of Baltica strongly influenced deformation style.

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JS08c - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow, heat production, and crustal thermal modeling of the Singhbhum Craton, eastern India

DOI: 10.57757/IUGG23-1098 - LINK

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Heat flow plays a vital role in estimating the lithospheric temperature distribution, which is an essential parameter in understanding the evolution and stabilization of the cratons. Heat flow is determined in the Mesoarchean Singhbhum Craton, one of the oldest cratons in the Indian shield, for the first time from seven locations. This enabled us to construct plausible 1-D crustal thermal models and to estimate mantle heat flow by considering a few crustal heat production/thermal conductivity models based on crustal structures from the geological/geophysical studies of the study region.

In the present study, detailed radioelemental abundances (Th, U, K) and heat production are measured for the Paleoarchaean gneiss (OMTG) and Singhbhum Granites (SBG) of the craton. The result shows that both OMTG and SBG, which cover most of the craton, have, in general, low radioelemental abundances and heat production with an average of 1.3 ± 0.2 mWm^{-3}. Heat flow ranges from 27-34 mWm^{-2}, with an average of 30 ± 3 mWm^{-2}, which is lowest than most of the cratons. Interestingly, the value is also half that observed in the Singhbhum Shear Zone (61 ± 2 mWm^{-2}), situated in its north. The 1-D thermal models indicate that mantle heat flow and Moho temperature range from 14-16 mWm^{-2} and 330-370 °C, respectively. These fall within the range observed for the Archaean cratons despite their lowest surface heat flow. It is mainly due to the distinct crustal heat production scenarios and upper crustal thermal conductivity profiles, which provide clues to understanding the craton formation.

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JS08c - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Mapping the thermophysical properties of Apennines rocks: Implications for the temperature state of the crust

DOI: 10.57757/IUGG23-2569 - LINK

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This laboratory study presents thermophysical rock measurements of 31 carbonates outcrop samples from the main geological formations of western Umbria (central Italy). Mineralogical analysis indicates that the formations under examination are mainly composed of calcite, with an abundance of quartz for some samples.

The conductivity and thermal diffusivity were determined with varying temperatures and both under dry and saturated conditions. Dry thermal conductivity measured with three different transient technique (optical scanning, transient plane source, transient hot wire method), differ by less than 10%.

At ambient temperature of 20 – 25°C, conductivity varies from 1.8 to 3.0 W/(mK) for samples with predominant calcite and show values greater than 3.6 W/(mK) for samples with larger quantities of quartz. For temperatures up to 200°C, conductivity for most of the samples decreases by about 30%.

Porosities reveal values of less than 5%. Theoretical mixing models based on the mineralogical composition and porosity were analysed to find the right fit with the measured values, with the possibility of extending the results to other parts of the world.

The results obtained from the study represent the basis for a more complete evaluation of the temperature trend with depth, useful for the evaluation of geothermal systems and for defining the rheological behaviour of the crust.

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JS08c - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Multi-well Horner Correction to Bottom Hole Temperatures in depleted oil and gas fields

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Depleted oil and gas fields contain a wealth of subsurface information that can be repurposed for geothermal, hydrogen, or carbon sequestration applications. The most common temperature measurement in oil and gas fields is the Bottom Hole Temperature (BHT). BHTs need to be corrected for disturbances to the thermal field by circulation of cool mud during drilling. The Horner correction is commonly used to correct temperatures back to in-situ conditions. It uses two and preferably three or more temperatures at the same depth measured at different times after mud circulation stops. This information is used to estimate an equilibrium temperature. Unfortunately, very few oil and gas wells have three or more BHT measurements that can be used in the Horner correction. For example, in southwest Weld County of Colorado which is part of the Denver-Julesburg (DJ) basin, there are only 12 wells out of more than 6,000 wells that have been Horner corrected because of the lack of same-depth measurements. In this study, we test whether BHT from nearby wells measured within a few tens of meters of each other in terms of depth can be used to make a Horner correction. We tested horizontal search radii of 400 m and 800 m and vertical search radii of 15 and 50 m. While results need to be screened for obvious errors such as positive Horner slope or unrealistically large correction, this method added hundreds of additional Horner corrected values.

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JS08c - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Petrophysical measurements and geophysical data integration for the geothermal potential evaluation of SW Poland.

DOI: 10.57757/IUGG23-1889 - LINK

Piotr Słomski[1], Łukasz Jasiński[1], Bartłomiej Grochmal[1], Kamil Bulcewicz[1], Agnieszka Oniszczuk[1], Marcin Dąbrowski[1]
[1]Polish Geological Institute - National Research Institute, Lower Silesian Branch - Computational Geology Laboratory, Wrocław, Poland

Polish Geological Institute is carrying out a project entitled "Geothermal atlas of the Sudetes and their foreland", which will fill the gap in knowledge about the geothermal potential of SW Poland. The project assumes the utilization of a large set of petrophysical measurements, together with logs from boreholes and surface geophysical data. More than 1000 samples were collected from outcrops and cores. This material was examined for K, U, and Th concentrations by gamma spectrometry. These results, together with density measurements, allowed for radiogenic heat map preparation. The values of radiogenic heat vary from nearly 0 to over 15 µW/m3, for Ślęża ophiolite massif and Karkonosze batholith, respectively. Thermal conductivity was measured by steady-state technique (FOX-50 apparatus) for over 100 samples. The homogenous rocks like granites show conductivity between ca. 2.8 and 3 W/mK, while other lithologies, i.e. gneisses, indicate values from ca. 1 to 4 W/mK. The thermal conductivities were also calculated based on the quantitative XRD analyses for 100 samples. The temperature logs from boreholes from the study area were digitised and analysed. A database containing 99 logs was prepared. The depth of these wells ranges from 201 to 2500 m, while the bottom temperature falls between 20 and 50 °C for the majority (71) of wells. The project is focused on continuing analyses for obtaining most complete view of the geothermal potential of SW Poland. At this stage, the Karknosze Granite Massif and part of the Intra-Sudetic Basin can be pointed as the most promising regions.

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JS08c - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Signature of climate changes in subsurface temperatures. A case study from Northern Bohemia, Czechia

DOI: 10.57757/IUGG23-1561 - [LINK]

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A 1.7 km long equilibrium temperature log from borehole Litoměřice, Czechia, measured 13 years after drilling provided a detailed knowledge of temperature gradient. Its most conspicuous feature is a gradual increase with depth from 22.0 K/km to 25.6 K/km within a lithologically homogeneous depth section 900–1700 m occupied by mica-schist. Conductivity and diffusivity was measured on drill-core samples from the upper part of this borehole section. Due to (i) the homogeneous lithology of mica-schist, (ii) a small scatter of the measured conductivity values and (iii) no trend in the dip angle of foliation, we assumed no depth trend of conductivity in the section 900–1700 m other than that resulting from pressure-temperature corrections. However, they introduce only a slight trend with values decreasing from 3.34 W/(m.K) at 900 m to 3.29 W/(m.K) at 1700 m, i.e. about 1.5 %, that cannot explain the observed 16% increase of the temperature gradient. We interpreted the increase as a transient feature generated by long-term ground surface temperature changes during the last glacial cycle. The inversion technique applied to the temperature log section 900–1700 m indicated the magnitude of the last glacial–Holocene warming of 13–15 K and the occurrence of a temperature minimum 15–20 ka. The long-term mean ground surface temperature of 1–2 °C suggests that the borehole site was permafrost-free for most of the last glacial cycle. The existence of about 100 m deep permafrost is possible in the coldest part of the last glacial.

The research is supported by the CSF 21-23196S

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JS08d - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

The Surface Heat Flow of Mars – and an attempt to measure it in-situ

DOI: 10.57757/IUGG23-0713 - LINK

Tilman Spohn[1]
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NASA's InSight mission [1] has installed the first geophysical observatory on Mars, including a seismometer, a magnetometer, sensors to track the rotation of the planet, an atmosphere science package and a heat flow probe HP^3 [2]. Cosmochemical and geophysical models [e.g., 3,4] suggest that the average Martian surface heat flow is around 25mW/m^{2}and may vary across the surface between 17 and 50mW/m^2. HP^3 was planned to use a small penetrator - nicknamed the "mole" – to install a string of temperature sensors up to a depth between 3m and 5m. A radiometer to measure the surface radiation temperature complemented the package. Sensors on the mole would measure the thermal conductivity as a function of depth. Depending on the final depth reached, temperature was to be measured daily for a period of months up to one Martian year. Unfortunately, the mole failed to penetrate to the required depth because of unexpected soil properties. Instead, it was used as a penetrometer and thermal probe to measure the thermal and mechanical properties of the top 40cm of the Martian soil. Inversion of the seismic recordings of Marsquakes allowed an estimate of the variation of the near surface temperature with depth and of the heat flow [5,6]. These estimates are consistent with the estimates from the earlier models [3,4].

[1] Banerdt et al. 2020 doi:10.1038/s41561-020-0544-y
[2] Spohn et al. (2022) doi: 10.1007/s11214-022-00941-z
[3] Plesa et al. (2016) doi:10.1002/2016JE005126
[4] Smreakr et al (2019) doi.org/10.1007/s11214-018-0563-9
[5] Khan et al. (2021) doi:10.1126/science.abf2966
[6] Drilleau et al. (2022) doi:10.1029/2021JE007067

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[6] Drilleau et al. (2022) doi:10.1029/2021JE007067

JS08d - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Investigations of potentially promising areas for the development of Renewable Geothermal Energy in Uzbekistan

DOI: 10.57757/IUGG23-0118 - LINK

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Anomalous areas of Heat Flow Density in Uzbekistan were identified at the stage of preliminary studies on the territory of the Republic. A Multidisciplinary Geophysical surveys (Seismic, Magneto telluric and Gravity exploration) now being implemented on the studied areas in Central Kyzylkum, Gissar and Aral regions. The goal of the development of geothermal resources are as follows: (1) develop a conceptual model to characterize the geology, geophysics and thermodynamics of resources; (2) develop, using this model, a cost-effective strategy for continuing exploration, delineating and evaluating a resource that provide depth and quality data necessary for making decisions regarding plans for the further development of promising geothermal areas in Uzbekistan. The results of geophysical studies, used in combination with geological data, allowed the construction of three-dimensional depth models of the structure of the studied areas with the location of the heat source and provide targets for test (exploration) drilling.

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JS08d - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Deep geothermal potential of Norway based on borehole data

DOI: 10.57757/IUGG23-3807 - LINK

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During the last decades, more than 30 relatively deep boreholes were drilled onshore in Norway. According to thermal logging, the highest temperatures (up to 28.2 °C at 800 m depth) were observed in the boreholes, located on the Svalbard archipelago which has signs of Quaternary magmatic activity. In contrast, the tectonically quiescent northernmost Norway is characterized by the lowest measured temperatures (slightly more than 9 °C at 650 m depth). The highest temperature in Central Norway (22.2 °C at 800 m depth) was measured on the small island close to the deep sedimentary basins in the Norwegian Sea. The southwestern part of Norway shows relatively low temperatures (e.g., 17.6 °C at a depth of 800 m near Stavanger). These low temperatures can be a result of groundwater flow that cools down the uppermost crust in this region. The area around the Oslo Fjord shows a complicated thermal pattern in the subsurface. There, at 800 m depth, the measured temperature ranges from 16 to 24 °C.

The described differences in the measured temperatures reflect the tectonic differentiation of the areas. A variation in the content of radioactive elements is also reflected by the measured temperatures. Consequently, the superposition of tectonic structure/evolution and compositional features controls the subsurface thermal pattern of Norway which is locally disturbed by the groundwater flow. Moreover, the paleoclimatic thermal effect is still present in these 300 to 1500-m-deep boreholes. Therefore, the above-mentioned factors must be evaluated in detail before planning the first deep geothermal site in Norway.

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JS08d - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Mapping Ireland's subsurface temperature: De-risking Ireland's Geothermal energy potential (DIG)

DOI: 10.57757/IUGG23-2878 - LINK

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The De-risking Ireland's Geothermal energy potential (DIG) project aims to de-risk borehole drilling costs to promote geothermal energy in Ireland. High-quality maps of the geothermal gradient and temperature are essential when assessing the geothermal potential of a region. However, determining geothermal potential is a challenge as direct measurements of in situ temperature are sparse and individual geophysical methods are sensitive to a range of parameters, not solely temperature. We develop a novel approach to determine the geothermal gradient using a joint geophysical-petrological thermochemical inversion (Fullea et al., GJI 2021), which requires thermal property data, seismic and additional geophysical datasets. The multi-parameter models produced by the integrated inversions fit the surface-wave, heat flow and additional data, revealing the temperature, lithospheric structure and geothermal gradient within the crust and mantle.

Here we present a new map of Ireland's subsurface temperature. Our new methodology produces results comparable to past temperature and geophysical measures, and enhances resolution. Critically the maps are consistent with borehole temperature measurements providing confidence in the results. Lithospheric and crustal thickness play a key control on the temperature gradient with areas of thinner lithosphere resulting in elevated geotherms. In some locations we observe geotherms elevated beyond expectations which result from high radiogenic heat production from granitic and muddy limestone rocks. This new methodology provides a robust workflow for determining the geothermal potential in areas with limited direct measurements. The final temperature model updates previous maps of Ireland and will be used for future geothermal exploration and utilisation.

The De-risking Ireland's Geothermal energy potential (DIG) project aims to de-risk borehole drilling costs to promote geothermal energy in Ireland. High-quality maps of the geothermal gradient and temperature are essential when assessing the geothermal potential of a region. However, determining geothermal potential is a challenge as direct measurements of in situ temperature are sparse and individual geophysical methods are sensitive to a range of parameters, not solely temperature. We develop a novel approach to determine the geothermal

gradient using a joint geophysical-petrological thermochemical inversion (Fullea et al., GJI 2021), which requires thermal property data, seismic and additional geophysical datasets. The multi-parameter models produced by the integrated inversions fit the surface-wave, heat flow and additional data, revealing the temperature, lithospheric structure and geothermal gradient within the crust and mantle.

Here we present a new map of Ireland's subsurface temperature. Our new methodology produces results comparable to past temperature and geophysical measures, and enhances resolution. Critically the maps are consistent with borehole temperature measurements providing confidence in the results. Lithospheric and crustal thickness play a key control on the temperature gradient with areas of thinner lithosphere resulting in elevated geotherms. In some locations we observe geotherms elevated beyond expectations which result from high radiogenic heat production from granitic and muddy limestone rocks. This new methodology provides a robust workflow for determining the geothermal potential in areas with limited direct measurements. The final temperature model updates previous maps of Ireland and will be used for future geothermal exploration and utilisation.

JS08d - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

The Global Heat Flow Database: New quality scheme and data release 2023

DOI: 10.57757/IUGG23-3313 - LINK

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Since 1963, the International Heat Flow Commission (IHFC) has been fostering and maintaining the compilation of the Global Heat Flow Database (GHDB). Over time, techniques and methodologies in heat-flow density determination evolved and called for frequent updates of the database. The increasing number of data and their diverse underlying methods also require an adequate and consistent evaluation scheme to assess the quality of the respective heat-flow density determination. Here, we provide the intermediate results of a collaborative, community-driven approach started in 2021 to set-up a new, authenticated GHDB. We document the new basic structure to report heat-flow data to the IHFC and present a newly developed consistent evaluation scheme. The quality scheme, for the first time, combines three independent quality criteria in one combined score, comprising the quantified uncertainty, the methodological quality, and the status of overruling effects. It allows a quick comparison of heat-flow data and reveals missing data or insufficient documentation at one glance. With the new quality scheme, users are enabled to select appropriate reliable heat-flow values for their specific purpose. The process to screen and update incomplete, wrong or empty database entries is ongoing and will last for a couple of years. The most recent intermediate update – the data release 2023 – contains data generated between 1939 and 2022. The data release contains 73,033 heat-flow data from 1,414 publications. 55% of the reported heat-flow values are from the continental domain (n ~40,082), while the remaining 45% are located in the oceanic domain (n ~32,951).

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JS09a - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Toward the effective use of an Earthquake Early Warning system for the high-speed rail network in Italy

DOI: 10.57757/IUGG23-2292 - LINK

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In the context of Earthquake Early Warning (EEW) applications, the high-speed rail networks are of particular interest due to their strategic role for private/public transportation. In Italy, in the frame of an industrial partnership, the University of Naples Federico II was recently commissioned by Rete Ferroviaria Italiana (RFI) S.p.A. to design, develop, and implement a prototype EEW system on the High-Speed Railway line between Rome and Naples. In case of a relevant earthquake, the system has the main goal of issuing an automatic alert that makes it possible to slow down high-speed trains, by resorting to a specific interface with existing signalling systems. The EEW methodology implements an evolutionary, P-wave based approach combining the single station and the network-based approaches. A probabilistic decision scheme for the alert declaration is implemented, accounting for the exceedance probability of a given PGA threshold value and for the uncertainty associated to the empirical scaling relationships. A final decision module evaluates whether and where the predicted PGA exceeds the established threshold and declares the alert at the nodes of the line where the most relevant shaking is expected. Here we will overview the basic principles and methodologies of the EEW platform and introduce a quantitative performance assessment, based on a retrospective off-line analysis of the system outputs. The performance analysis allows evaluating both the system rapidity in providing alerts and the quality/reliability of these predictions and represents the key element for stakeholders and end-users, to properly configure and setup the operational system.

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JS09a - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

ShakeAlert V3.0: Expected Performance in Large Earthquakes

DOI: 10.57757/IUGG23-2075 - LINK

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[5]Univ. of Washington, Earth and Space Sciences, Seattle, USA

The ShakeAlert Earthquake Early Warning (EEW) System issues public alerts in the states of California, Oregon, and Washington with a mission of reducing injuries and property loss from damaging earthquakes. Shortly after ShakeAlert went live in 2019, the Ridgecrest earthquake sequence provided a major test of the system's capabilities. For several reasons ranging from the inherent limitations of EEW, to data telemetry and algorithm deficiencies, ShakeAlert failed to provide useable warnings for most locations where people were in danger for both the M6.4 and M7.1 mainshocks [Chung et al. 2020]. Since Ridgecrest, the ShakeAlert algorithm development and testing team has improved all components of the software and evaluation mechanisms, resulting in dozens of updates to the operational system. We expect version 3.0 of the ShakeAlert software to go live in the summer of 2023. This version is the first to include a geodetic algorithm aimed at large subduction ruptures in Cascadia. We will present various evaluations of expected performance of ShakeAlert in large earthquakes from offline testing. For instance, over 70% of instrumented sites that experienced strong or greater shaking in the 2016 M7.1 Kumamoto earthquake could have received at least 10 s of warning before strong shaking began using the ShakeAlert MMI 4 contour product depending on delivery latencies. Similarly, during the 2022 M6.4 Ferndale earthquake in Northern California, the real-time system published the MMI 4 contour product more than 10 s before strong shaking at about 50% of instrumented sites.

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JS09a - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Rollout of central America's national public earthquake early warning systems

DOI: 10.57757/IUGG23-1021 - LINK

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The ATTAC project, or Alerta Temprana de Terremotos en América Central, aims to establish public earthquake early warning (EEW) systems in Central America. The region experiences frequent subduction and shallow crustal earthquakes and has a vulnerable building stock, along with a rapidly growing population density. EEW can reduce the fatalities and injuries that occur during strong earthquakes. The ATTAC project is building national EEW systems at seismic agencies in each of Guatemala (INSIVUMEH), El Salvador (MARN), Nicaragua (INETER), and Costa Rica (OVSICORI-UNA), with the collaboration of SED at ETH Zurich.

The EEW systems are based on the ETHZ SeisComP EEW (ESE) add-on modules and include the Virtual Seismologist and FinDer algorithms. The project has deployed 70 low-latency accelerographs across the region and has implemented performance-tracking tools to monitor the network and EEW results in terms of accuracy and speed. The ESE dissemination module allows to select the best of the EEW solutions and to deliver targeted alerts via a mobile application and digital TV.

Data analysis of the mobile application has shown promise (74% of users notified in 5 seconds). Although the number of active recipients is in the low thousands, it is scaling up. We demonstrate successful EEW for recent earthquakes with delay from event initiation to alert dissemination ranging from 10 to 15 seconds for shallow onshore seismicity and from 20 to 25 seconds for offshore or deep events. We focus on false alerts with software and configuration optimizations and establishing best practice in network management.

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JS09a - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

A regional hazard-based approach for seismic network design for earthquake early warning

DOI: 10.57757/IUGG23-2978 - LINK

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[2]*California Institute of Technology, Geological and Planetary Sciences, Pasadena, USA*

Seismic network optimization for Earthquake Early Warning (EEW) differs from the more general mission of regional monitoring. A network designed for EEW must prioritize speed of detection, the magnitude and rate of occurrence of likely earthquakes, and the location of seismic sources relative to population centers. A recent analysis by Böse et al. combines these elements in an end-to-end analysis for EEW monitoring in Switzerland. They sample from the combined instrumental and historical catalog for the region to evaluate hazard and losses. We have developed a similar approach based on gridded USGS National Seismic Hazard Map (NSHM) inputs. Hazard maps include catalog and historical seismicity, but also synthesize geologic and geodetic slip rates, geophysical inputs and paleoseismic event information. They are also extensively reviewed. The US NSHM maps are extrapolated from hazard curves calculated on a grid. We extract from the hazard curves the return time at a given shaking intensity, e.g. PGA=0.1 g, as a proxy for how often a station at that location will contribute to EEW detection from nearby earthquakes. The ground motion intensity corresponds to an approximate magnitude and location distribution that can be used in a forward calculation with attenuation to find impact on population centers. Stations near active faults generally minimize detection time and maximize warning time. Stations with shorter return times contribute more often and are generally near larger earthquakes. The best station distribution will give the greatest number of people the most useful warning.

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A deep learning analysis of seismic waveforms for the estimation of Peak Ground Acceleration using single station

DOI: 10.57757/IUGG23-2005 - LINK

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The identification and rapid estimation of earthquake parameters such as Peak Ground Acceleration are crucial for Earthquake Monitoring and Earthquake Early Warning especially for strong earthquakes. The conjugation of seismic waves with the layers of geological media of varying elastic properties results in a varying PGA from site to site. The local site effects heavily influence the PGA values , for instance if the site is composed of soft-sediments the amplification within the ground motion is more prominent than that of a rocky terrain or very firm sediments. We use deep learning to model these nonlinearities to identify the PGA value of the incoming earthquake signal. We use the global data STanford EArthquake Dataset, STEAD benchmarked for Machine Learning applications. The proposed model architecture may be considered as a priliminary prototype that could be adapted into EEW systems for effective emergency response.

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JS09b - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Feasibility study for an Integrated Earthquake and Tsunami Early Warning System: application to a synthetic case in the Messina strait

DOI: 10.57757/IUGG23-2428 - LINK

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[1]Università degli studi di Napoli "Federico II", Dipartimento di Fisica "Ettore Pancini", Napoli, Italy
[2]Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Roma, Italy

Nowadays, Tsunami Early Warning Systems (TEWS) issue the first alert between three and five minutes after the occurrence of a potentially tsunamigenic earthquake. For offshore earthquakes, for which a significant network azimuthal gap limits the accuracy of standard techniques for source location, this time is spent to obtain stable estimations of the event magnitude and depth. This large warning time affects the efficiency of TEWS for near-coastal large earthquakes. Recent developments in Earthquake Early Warning Systems (EEWS) mitigates this issue. Here, we consider a P-wave, shaking-forecast based EEW method (Zollo et al., 2023) to provide fast and accurate estimations of event location and magnitude along with the Potential Damage Zone (PDZ). As a first test of a combined E- and T- EWS, we applied the method by playing-back the simulated records of two events of Mw 6 and 7 in the Messina strait, with source characteristics that mimic the 1908 Messina earthquake. The events are simulated at the INGV and RAN seismic stations along the Sicily and Calabria coasts. We estimated stable and accurate hypocenter locations and magnitude determinations in 20-25 seconds for both events. The shape of the PDZ obtained after 30 s from the earthquake origin well reproduces the geometry of the rupture surface. These first results show that combining EEWS and TEWS can speed up the tsunami forecasting, thus increasing the lead-time available for actions to protect the exposed population.

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JS09b - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Reducing false tsunami early warnings by combing high-rate GNSS-detected ground movement and ionospheric disturbance

DOI: 10.57757/IUGG23-3789 - LINK

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The current tsunami early warning systems usually issue alarms once large undersea earthquakes are detected, inevitably resulting in false warnings since there are no deterministic scaling relations between earthquake size and tsunami potential. In this study, we attemp to characterize tsunami potential more precisely to avoid uncessary alarms by analyzing both the co-seismic displacement waveforms (CDWs) and ionospheric disturbances (CIDs) as detected by high-rate Global Navigation Satellite System (GNSS) observations. We examined CDWs and CIDs of three megathrusts including the 2014 Mw 8.2 Iquique, the 2015 Mw 8.3 Illapel, and the recent 2021 Mw 8.2 Alaska events. We found that CDWs generated by the 2021 Mw 8.2 Alaska event indicating ruptures far away from the trench and CIDs near the epicenter event were significantly weaker than those of the two Chilean events, despite having similar earthquake magnitudes. Furthermore, the propagation direction of CIDs from the Mw 8.2 Alaska earthquake also confirmed slips toward the deeper seismogenic zone, consistent with CDWs infer and both implied less seafloor uplift and hazardous flooding. Our work sheds light on incorporating both GNSS-based CDWs and CIDs for more trustworthy tsunami warning systems.

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JS09b - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Real-time GNSS perspectives for novel natural hazards early warning systems: crustal deformation and ionospheric perturbations

DOI: 10.57757/IUGG23-0749 - LINK

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Natural hazards (earthquakes, tsunamis, volcanic eruptions, *etc.*) have devastating human and economic consequences. Their early detection and characterization lead to timely evacuations, which are critical for significantly reducing casualties and economic cost. However, traditional early warning systems (EWS) are limited by inherent challenges. We present two novel GNSS-based methods that are viable augmentations to EWSs.

The first, developed at Central Washington University, monitors earthquakes and tsunamis globally, based on low-latency in-situ measurements from ~1800 globally-distributed receivers. The system can rapidly characterize moment release, as ruptures unfold. Position time series are continuously streamed as local 3D coordinates into monitoring algorithms, and also broadcast for third-party use. The system's average latency is ~0.5 seconds, and its average position variance remains below 8 cm. This system captured the 2019 M7.1 Ridgecrest earthquake on 12 nearby stations within 22 seconds after onset; the system's estimates of co-seismic deformation were within 10% of the post-processed "true" values.

In addition, another remote sensing technique leverages ionospheric total electron content (TEC) measurements. Indeed, through mechanical coupling, large air and ground perturbations at the Earth's surface propagate up as low-frequency atmospheric waves. Eventually disrupting the ionosphere, those waves can be observed through ground-based GNSS measurements. In particular, we present the GUARDIAN system, developed at JPL (https://doi.org/10.1007/s10291-022-01365-6), which runs in near-real-time (latency < 5 minutes) using multi-GNSS data from 80 stations from JPL's GDGPS network around the Pacific Ocean. GUARDIAN outputs TEC time series to a user-friendly public website, and are routinely validated against traditional ionospheric post-processing techniques.

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JS09b - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Development of a fault model estimation method based on real-time MCMC and its implementation to a real GNSS network

DOI: 10.57757/IUGG23-0751 - LINK

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Rapid estimation of the coseismic fault model for medium-to-large-sized earthquakes is key for disaster response. To estimate the coseismic fault model for large earthquakes, the Geospatial Information Authority of Japan and Tohoku University have jointly developed a real-time GEONET analysis system for rapid deformation monitoring (REGARD). REGARD can estimate the single rectangular fault model and slip distribution along the assumed plate interface. The single rectangular fault model is useful as a first-order approximation of a medium-to-large earthquake. To obtain a more robust fault model with its estimation uncertainties, we developed a new method to estimate the coseismic fault model and model uncertainties in real-time based on the Bayesian inversion approach using the Markov Chain Monte Carlo (MCMC) method. In general, MCMC requires a long mixing time to obtain posterior probabilities, but the developed method can obtain a solution within about 20 seconds after the permanent displacement is acquired, thanks to parallel tempering and other computational efficiency improvements. The developed method has already been implemented in REGARD and has been successfully demonstrated to obtain real-time solutions for several moderate-size earthquakes. Tohoku University and the GSI are also developing a fast estimation method of slip distribution at plate boundaries using MCMC. The presentation will include a more detailed discussion of the advantages of using MCMC to estimate the slip distribution at the plate boundary.

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JS09c - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Providing transboundary flood forecasts with the Global Flood Awareness System (GloFAS)

DOI: 10.57757/IUGG23-4370 - LINK

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The rise of early warning systems is enabling proactive responses to natural hazards such as floods. However, such systems could have restricted user access, limited geographical coverage, and either minimal or absent predictions in areas with few observations. In the case of flooding, the costliest natural hazard, this may translate into issues such as a lack of insight into the hydrological situation in poorly gauged areas, and downstream regions having limited information on upstream river conditions. The Global Flood Awareness System (GloFAS) addresses these issues by providing a global hydrological forecast and monitoring system that produces forecasts even in poorly gauged areas, and is open access and transboundary. Fully operational as part of the European Union's Copernicus Emergency Management Service since 2018, the system provides flood forecasts up to 30 days lead time and monthly seasonal streamflow outlooks via the GloFAS online map viewer. Complementary information on forecast skill and hydrological model performance is also made available to aid users' interpretation and understanding of forecast quality, alongside regional flood impact assessment estimates. Here, we give an overview of the GloFAS forecasting system and the available products, including an introduction to the GloFAS map viewer products. Lastly, we also present the GloFAS data made available on the Copernicus Climate Data Store, which alongside the forecasts includes sub-seasonal and seasonal reforecasts and a reanalysis dataset covering over 40 years. We also present our recently created training material to help users access and explore the GloFAS data from the Climate Data Store.

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JS09c - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Developing a user-focused flood forecast product for a continental-scale system

DOI: 10.57757/IUGG23-3275 - LINK

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[7]Loughborough University, Department of Geography, Loughborough, United Kingdom

Early warning systems can help mitigate the damage caused by floods by increasing preparedness. However, to be useful in the event of a flood the products from these early warning systems must be actionable. The European Flood Awareness System (EFAS), part of the European Commission's Copernicus Emergency Management Service, provides complementary flood forecasts to EFAS partners across the whole of Europe. The EFAS 'post-processed forecast product' is generated for the location of approximately 1600 river gauge stations where sufficient historic and near-real time river discharge observations are available. The aim of this product is to provide an error-adjusted forecast up to a maximum lead-time of 15 days. Recently, the temporal resolution of this product has increased from daily to 6-hourly timesteps providing an ideal opportunity to identify future developmental priorities. Following a workshop with the EFAS partners a roadmap for future developments of the EFAS post-processed forecast product was designed to ensure the user's changing requirements are satisfied. Here, we present this roadmap, and the results of the first stages, which include improvements to the post-processing methodology to better account for the different hydroclimatic regimes across Europe, and changes to the post-processed forecast product to make it more locally relevant and useful to the EFAS Partners.

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JS09c - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Empirical findings on communicating the uncertainty of weather forecasts and warnings

DOI: 10.57757/IUGG23-4700 - [LINK]

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[4]*Freie Universität Berlin, Institut für Meteorologie- HErZ, Berlin, Germany*

In recent decades, meteorology has made great progress in producing reliable probabilistic forecasts. However, forecasts and especially weather warnings continue to be communicated almost exclusively in deterministic terms. The failure to communicate probabilistic information not only hinders shared decision-making between meteorologists, organisations and the public. This practice also does not take into account that probabilistic information may well be preferred by laypersons, may increase confidence in forecasts and may lead to better decisions. For the practical use of uncertainty information, it must be clarified, for example, under which conditions it is helpful, how it should be processed verbally and graphically, and which institutional and operational questions must be clarified.

In this presentation, we present exemplary results of our own social science studies within the framework of the WEXICOM project of the Hans Ertel Centre for Weather Research (HErZ) on the following questions: What do users know about the uncertainty of forecasts? What attitudes do users have towards providing uncertainty information, e.g. do they want to receive this information? How is uncertainty communicated verbally? Which graphical representations do users prefer? At what probability would users react? What influence do space and time references of uncertainty information have on the understanding of the information and how do they influence the use for decisions? Finally, we present the challenges and new approaches for the communication and use of uncertainty information in weather forecasting.

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JS09c - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Near Real-time Flash Flood - Landslide Early Warning System Using Combined Low-cost Sensors and Rain Radar Composites In Northeastern Thailand

DOI: 10.57757/IUGG23-3516 - LINK

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Flash floods and landslides are severe natural hazards caused by heavy rainfall. When aiming for a robust real-time early warning system, rain radar products are key for tracking heavy storms and quantifying hydrological behavior in mountainous catchments. The precision of radar rainfall estimates remains an essential concerns in the application of radar-based observation. Finally, composite radar products of 2 or more rain radar observation are required to improve the quality of the radar product to visualize the distribution and movement of precipitation over a large area.

In our research, we aim to build a near-real time flash flood and landslide EWS for a hazard-prone Khao Yai NP in northeastern Thailand. Specifically, we evaluate low-cost sensors, linked to high resolution radar rainfall observations. These sensors measure a.o. soil moisture, precipitation, water and air pressure, and transmit real-time data via NB-IoT mobile signals. The rain gauge rainfall data will be merged with weather radar data to compute radar rainfall bias adjustment for preparing high-quality gridded rainfall over the study area. Moreover, we investigate the controlling factors influencing the quality of radar composites over and quantify the rain radar composites. The results indicated that specific quality indexes could be used to identify areas with inaccurate or unreliable raw data. The low-cost sensors and radar composites are subsequently used in spatially distributed models that are the basis of an early warning systems that is under development in this hazard-prone mountainous region.

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JS09c - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

The Seismically-Induced Submarine Landslides and their Chain Disasters since 1900: A Global Review

DOI: 10.57757/IUGG23-3361 - LINK

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Submarine landslides represent a significant marine geohazard that can be triggered by multiple factors, but most commonly by earthquakes. Seismically-induced submarine landslides (SISLs) could further trigger tsunamis or be converted into high-speed moving turbidity currents, generating the chain disasters and resulting in the destruction of coastal and submarine infrastructures. Unfortunately, most earthquakes, including many of the devastating earthquakes, occurred in subduction zones or other plate boundary fault systems which are near enough to the coast. Therefore, SISLs often provide a short tsunami warning time. However, the SISLs and their chain disasters still remain poorly understood, and are seldom considered in tsunami warnings. This study reviews various aspects of SISLs, from their occurrence mechanisms and dynamics, to submarine slope stability assessment under seismic shaking. We summarize the chain disasters caused by SISLs globally since 1900 including the chain of earthquake - submarine landslides - tsunami and the chain of earthquake - submarine landslides - turbidity currents - cables break. For the first time, primary characteristics of these SISLs, such as volume, initial water depth and slope, and distance from the coast and seismogenic fault, are collected and summarized in detail. We investigate the quantitative relationships between earthquake magnitudes and distances between the SISLs and the seismogenic faults and calculate the ground acceleration (PGA) generated at the SISLs position during the corresponding earthquake. The results of this study are useful for increasing the understanding of SISLs and their chain of cascading events, which is essential for local tsunami warnings and hazard prevention.

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JS09d - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Predicting the future earthquake early warning effectiveness of the planned seismic network in Chinese mainland

DOI: 10.57757/IUGG23-5004 - LINK

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Institute of Risk Analysis- Prediction and Management Risks-X, Shenzhen, China

The China Earthquake Administration (CEA) has launched an ambitious nationwide earthquake early warning (EEW) system project, which will consist of approximately 15,000 seismic stations and be the largest EEW system in the world. In 52%, 30% and 17% of Chinese mainland, the inter-station distance will soon be smaller than 50 km, 25 km and 15 km, respectively. The effectiveness of the EEW system expected inside Chinese mainland can be quantified via the metric given by the radius of the blind zone (no-warning zone). Using theoretical network-based method, we generate the spatial distribution of the blind zone radii predicted for the new seismic network based on its configuration. The densified new seismic network is expected to have excellent EEW performance from the perspective of blind zone. The area covered by blind zones that are smaller than 30 km will soon rise from 1.6% to 24.3% inside Chinese mainland, which means that the area will increase by 2.6 million km^2. We claim that every 1,000,000 RMB (158,000 USD) invested to densifying the planned network will increase the area where the blind zone radius is smaller than 30 km by 3,000 km^2. Continuing to increase the density of stations in some key regions with the blind zone radii ranging from 20 to 40 km is still necessary to control the unexpected expansion of blind zones due to the possible (and common) stations failure. Our investigation provides a useful reference for the real functioning and further optimization of the EEW system in Chinese mainland.

The China Earthquake Administration (CEA) has launched an ambitious nationwide earthquake early warning (EEW) system project, which will consist of approximately 15,000 seismic stations and be the largest EEW system in the world. In 52%, 30% and 17% of Chinese mainland, the inter-station distance will soon be smaller than 50 km, 25 km and 15 km, respectively. The effectiveness of the EEW system expected inside Chinese mainland can be quantified via the metric given by the radius of the blind zone (no-warning zone). Using theoretical network-based method, we generate the spatial distribution of the blind zone radii predicted for the new seismic network based on its configuration. The densified new seismic network is expected to have excellent EEW performance from the perspective of blind zone. The area covered by blind zones that are smaller than 30 km will soon rise from 1.6% to 24.3% inside Chinese mainland, which means that the area will increase by 2.6 million km^2. We claim that every 1,000,000 RMB (158,000 USD) invested to densifying the planned network will increase the area where the blind zone radius is smaller than 30 km by 3,000 km^2. Continuing to increase the density of stations in some key regions with the blind zone radii ranging from 20 to 40 km is still necessary to control the unexpected expansion of blind zones due to the possible (and common) stations failure. Our investigation provides a useful reference for the real functioning and further optimization of the EEW system in Chinese mainland.

JS09d - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Low-cost methods for early warning to geohazards

DOI: 10.57757/IUGG23-4317 - LINK

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The northern boundary region of Bangladesh and neighbouring North-East Indian states of Meghalaya and Assam are capable of producing large (M≥7) to great (M≥8) earthquakes as historical evidence shows. Such earthquakes can cause havoc and wide spread damage in densely populated cities of Bangladesh including the capital city of Dhaka. If an earthquake monitoring system can be installed in towns near Bangladesh-India border, a warning time of several seconds will be available before the earthquake waves reach Dhaka city. This time may be used for quick safety measures such as taking appropriate shelter, building evacuation, shutting off gas etc. A low-cost seismic accelerometer with alert system and backup battery has been manufactured using available low-cost accelerometer sensor and data acquisitions system. It sends warning message using mobile network whenever the acceleration exceeds selected threshold value. Because of its low cost it can be easily deployed in large numbers and can provide early warning for distant large magnitude earthquakes. In recent years, landslides have emerged as recurring natural hazards in hilly urban areas of Chittagong and Rangamati causing human casualties. A low-cost computational method based on rainfall data and hill-slope data is briefly discussed. To monitor vulnerable hill slope, low-cost inclinometer can also be assembled which will send a warning message when there is significant soil movement resulting in tilting of the inclinometer. Early warnings made possible by installing such low-cost devices can play a major role in reducing casualties and property losses during a major earthquake or landslide event.

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JS09d - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Reviewing the multi-hazard concept. Application to volcanic islands.

DOI: 10.57757/IUGG23-1490 - [LINK]

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Because of their social, economic and political contexts, and their intrinsic multi-hazard nature, volcanic islands are one of the most vulnerable environments, where natural hazards (volcanic and non-volcanic) tend to occur in a simultaneous way causing cascading effects. To date, most of the scientific knowledge, as well as hazard assessment and risk management protocols focus on individual hazards and risks, while it remains a challenge to correctly predict the outcomes and impacts of a multi-hazard scenario where several hazardous phenomena may interact in simultaneous or consecutive ways. The multi-hazard concept originated in the 1990s in the international political context precisely to respond to this need. After its first appearance, different–and often, contradictory–usage perspectives of the multi-hazard concept have been increasingly put forward, thus making it difficult for this new approach to be fully implemented into disaster reduction policies. The present study assesses the current status of the application of the multi-hazard approach in existing risk management systems, and proposes future improvements to disaster risk reduction. It also presents the multi-hazards to which volcanic islands are exposed and analyses their potential impacts, taking the Canary Islands as a case study. In doing so, it emphasizes the need to establish a cross-sectoral, climate change-oriented, socially-inclusive, multi-risk management system, based on scientific knowledge and linked to critical societal demands and solutions.

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JS09d - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

La Soufriere Volcano eruption 2020-21 - testing the integration of Community Volcanic Emergency Plans and national EWS in St. Vincent

DOI: 10.57757/IUGG23-5034 - LINK

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Caribbean Small Island Developing States are exposed to a multiplicity of natural hazards and St. Vincent and the Grenadines, home of La Soufriere Volcano, is one of the most disaster-prone. Overcoming the challenges associated with operating a geophysical monitoring network aimed at providing early warning of an impending eruption has required the use of several strategies. A key component of these have been building partnership with local disaster management officials and community members in high-risk zones on the volcano.

We have worked with disaster management officials and community members to help them develop Community Volcano Emergency Plans (CVEPs) that incorporated multi-hazard mapping, vulnerability and capacity assessments, training and equipping of Community Emergency Response teams and testing of plans through simulation exercises. Activities such as evacuation routing, identification of shelters and muster points and stocking of emergency supplies were all integral elements in these plans.

CVEPs aim to effectively illustrate the role of and actively engage with monitoring scientists, disaster management agencies and citizens in dealing with volcanic emergencies. The 2020–2021 eruption of La Soufrière volcano served as an important test to the entire system. The eruption involved a series of explosions from 9–22 April 2021 that were preceded by three months of effusive activity, which commenced with a very low level of detected unrest. It occurred against the backdrop of the Covid pandemic which presented multiple challenges to effective response.

In this presentation we share our experience of integrating community response with EWS and review its performance during the 2020-21 eruption.

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JS09d - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Lahar detection at Santiaguito using Machine Learning techniques

DOI: 10.57757/IUGG23-4336 - LINK

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The Santiaguito Volcanic Complex is located in Guatemala's Western Volcanic Highlands, along the westernmost section of the Central American Volcanic Arc. Santiaguito presents multiple hazards (including pyroclastic density flows, lava flows, lahars, explosions and debris avalanches) to the local population, which numbers 1.6 million people within the 30 km2 around the volcano. Lahars are mixtures of water and pyroclastic debris that includes gases which can rapidly initiate and flow at speeds of tens of meters per second down wide barrancas (canyons) making them highly destructive. Lahar occurrence strongly correlates with rainfall at the volcano and they are commonplace in the long rainy season. They pose a great hazard to local inhabitants who regularly cross the channels as they live and work on farms on or near the flanks of the barrancas. INSIVUMEH, the national seismic and volcano monitoring agency, has recently built a network of 10 seismic stations that can monitor these flows, in collaboration with external agencies. Using the seismic data from the 2022 rainy season we have built a Lahar catalogue. We supplement the dataset by adding synthetic Lahar waveforms to it, informed by the existing recorded events. We then use the hybrid catalogue to develop a Convolutional Neural Network Lahar detector, always testing on real events. We test using different input lengths to find an ideal timeliness/accuracy ratio for Lahar early warning. We plan to extend the method for Lahar location tracking. We expect the method to be portable to other volcanic areas.

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JV03a - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

Anatomy of the tsunami and Lamb waves-induced ionospheric signatures generated by the 2022 Hunga Tonga volcanic eruption

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As tsunamis propagate across open oceans, they remain largely unseen due to the lack of adequate sensors. To address this fundamental limitation of existing tsunami warnings, we investigate Global Navigation Satellites Systems (GNSS) data to monitor the ionosphere Total Electron Content (TEC) for Traveling Ionospheric Disturbances (TIDs) created by tsunami-induced internal gravity waves (IGWs). The approach has been applied to regular tsunamis generated by earthquakes, while the case of undersea volcanic eruptions injecting energy into both the ocean and the atmosphere remains mostly unexplored. With both a regular tsunami and air-sea waves, the large 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption is a challenge. Here, we show that even in near-field regions (1000-1500km), despite the complex wavefield, we can isolate the regular tsunami signature. We also highlight that the eruption-generated Lamb wave induces an ionospheric disturbance with a similar waveform and an amplitude spatial pattern consistent with IGW origin but with a quasi-constant propagation speed (~ 315m/s). These results imply that when GNSS-TEC measurements are registered near an ocean bottom pressure sensor, they can help discriminating the regular tsunami from the initial air-sea waves appearing in the sensor observations.

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JV03a - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

Instantaneous and Adjusted Radiative Forcing and Volcanic Cloud Evolution of the January 2022 Hunga Tonga-Hunga Ha'apai (HTTH) Eruption

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We modified the regional WRF-Chem model to study the evolution and radiative forcing of the January 2022 HTHH eruption. We use the Single Moment 5-class cloud microphysics scheme to handle the water in the troposphere and stratosphere. The Rapid Radiative Transfer Model (RRTMG) for shortwave (SW) and longwave (LW) radiation is used for radiative transfer calculations. We simultaneously inject SO_2 and water vapor at 35 km and conduct simulations in the (50S-10N) latitude belt for three months with 25 km spatial resolution. Initially, the volcanic cloud cools by thermal radiation and descends. The instantaneous radiative forcing was calculated by double call at the same meteorological fields. We found that in a month, the water vapor radiative forcing averaged over the latitude belt at the top of the atmosphere (TOA) reaches -0.016 W/m^2. The water vapor solar forcing is positive but two orders of magnitude smaller than LW forcing. Sulfate aerosol develops almost immediately after the injection. In two months, the sulfate SW forcing at TOA reaches -0.3 W/m^2. The sulfate LW forcing at TOA is positive but does not exceed 0.07 W/m^2 averaged over the domain. The volcanic cloud is cooling from the top at 0.1 K/day and warms from the bottom at 0.06 K/day. Thus, in our calculations, water vapor, nonuniformly distributed in the upper and middle stratosphere, cools the planet, although it is a greenhouse gas. However, the radiative effect of water vapor is 20 times smaller than sulfate aerosols.

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JV03a - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

Long-term development of the stratospheric water vapour enhancement from the Hunga Tonga eruption

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The eruption of the Hunga submarine volcano on 15 January 2022 was likely the most explosive event of the modern observational era. Its plume reached altitudes over 50km over ground and carried large amounts of water vapor into the typically dry stratosphere. Simulations with the Chemical Lagrangian Model of the Stratospheric (CLaMS) could demonstrate that the behaviour of the injected water vapour could reproduce observations by the Microwave Limb Sounder (MLS) among others for about a month (Khaykin et al., 2022). After one year water vapour in the upper stratosphere is still significantly enhanced compared with the longtime record according to satellite observations by MLS. Here we investigate also the water vapour distribution over this period using a continuation of this CLaMS simulation based on ERA-5 reanalysis data.

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JV03a - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

The 2022 Hunga volcano eruption from the multi-technological perspective of CTBT monitoring

DOI: 10.57757/IUGG23-1802 - LINK

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The Comprehensive Nuclear-Test-Ban Treaty (CTBT) prohibits all nuclear explosions. For detection of potential non-compliance, the International Monitoring System (IMS) with 321 stations is being installed. The International Data Centre in Vienna provides standard data products. The discrimination of the event character is the responsibility of the State Signatories who are encouraged to make use of additional data, so called national technical means.

The explosive eruption of the Hunga Volcano on 15 January 2022 provides an ideal test case for reviewing established methods to analyse source processes. This is due to its enormous force and its explosive source mechanism close to an expected one but still featuring significant differences. Discriminating different kinds of explosive sources such as a nuclear test and a volcano eruption is a key task in the CTBT context.

We apply standard techniques to all four data types, i. e. three waveform technologies (seismology, infrasound, and hydroacoustic) and atmospheric transport modelling of radionuclides. Assessing the potential of these methods to discriminate a source, we can show that they work very well to identify, investigate, and discriminate an event of interest. During discrimination we could not only exclude a shear-source (i.e. an earthquake) but also distinguish the volcanic explosion in contrast to a man-made explosion. However, some tasks remain difficult (e.g. strength and therefore yield estimation). In addition to evaluating the methods, we could relate our results with specific phases of the volcanic processes providing a more detailed insight of what happened during the eruption.

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JV03a - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

MERMAID Autonomous Drifting Instruments Capture Sustained and Coherent Hunga Tonga Hunga Ha'apai Eruptive Signals Propagating Across the South Pacific

DOI: 10.57757/IUGG23-3728 - LINK

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[1]Princeton University, Department of Geosciences, Princeton, USA
[2]University of Bristol, School of Earth Sciences, Bristol, United Kingdom
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More than two dozen MERMAIDs floating in the South Pacific recorded the hydro- and seismo-acoustic signals excited by the 15 January 2022 Hunga Tonga Hunga Ha'apai eruption. MERMAID, short for Mobile Earthquake Recording in Marine Areas by Independent Divers, is an oceanic mid-column float designed to autonomously record and report high-frequency (~1 Hz) teleseismic P waves useful for global tomography. MERMAID is a diver: it records acoustic data streams via its hydrophone at depth and surfaces roughly once a week to transmit those data via satellite. Its algorithms prioritize the isolation of short (minutes-long) data segments containing P waves. However, MERMAID's data buffer remains retrievable via two-way Iridium communication for one year. We made first-of-their kind multi-hour requests to capture the eruptive process recorded across the South Pacific Plume Imaging and Modeling array. We primarily focus on the high-frequency (5+ Hz) T-wave signals, broadly described as a double-peaked onset followed by a sustained high-SNR ``rumble'' lasting roughly 30 minutes. Many MERMAIDs across the array — at varied distances and backazimuths — exhibit high correlations of this main wave packet, however some do not. We investigate the reasons for intra-array variability in the shape and amplitude of the main wave packet, with particular emphasis given to understanding the role of bathymetry. Finally we discuss the public MERMAID data set currently available through EarthScope, and their accompanying new metadata standard called GeoCSV, which was recently approved for implementation by the FDSN Working Group 5 to track our, and other, moving seismometers.

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JV03a - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

Worldwide seismic observations of low frequency signals generated by the 15 January 2022 Hunga-Tonga eruption

DOI: 10.57757/IUGG23-1979 - LINK

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The eruption of the Hunga-Tonga volcano produced a high-energy explosion that was recorded globally by different scientific instruments, including broad-band seismometers. Seismic data recorded on global seismic networks are used to explore three main topics; the time evolution of the eruption, the atmospheric waves revolving around the Earth and the low-frequency, long-lasting signals recorded worldwide in the hours after the main event. From the inspection of the data we can assess that the eruption started on January 15 around 04:05 UTC, several minutes before the origin time reported in the seismic catalogs and included two large explosions at 05:30 and 08:35. As for the atmospheric waves, their energy was enough to be detected seismically during more than two complete circumambulations of the Earth, during a time span of three and a half days. The most notable seismic feature has been the low-frequency signals detected over several hours and interpreted as resulting from the excitation of Earth normal modes. To our knowledge, there are no previous examples of atmospheric-solid Earth coupling over such a long time interval and only two examples of normal mode excitation following volcanic eruptions, identified for the 1982 El Chinchón and the 1991 Mount Pinatubo eruptions.

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JV04a - Volcano Seismology (IAVCEI, IASPEI)

Usage of rotational sensors on volcanoes

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Typical volcano-seismic signals on volcanoes include LP events, VT events and tremor. These events are detected and listed in catalogs as well as located and interpreted in the context of the volcano. Normally seismometers are used for these tasks. However, besides the translational ground motion, these events also generate rotational ground motion. Within this presentation we will highlight how rotational sensors can be used in this context. Following a few huddle tests in the field, we have installed the sensors in volcanically active regions such as Mount Etna and several interesting sites in Iceland. As a community effort we also started the python package TwistPy, to which more codes will be added in the future.

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JV04a - Volcano Seismology (IAVCEI, IASPEI)

Precursory volcanic tremor and eruptive phases of the 2021 Geldingadalir eruption revealed through deep clustering

DOI: 10.57757/IUGG23-3429 - LINK

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[2]*University of Potsdam, Institute of Geosciences, Potsdam, Germany*
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Analyzing and interpreting continuous seismic data in a timely manner, which could provide the potential for an operational forecast is an important goal in volcano seismology. Among these, detecting and understanding the precursors of volcanic eruptions have a key role in volcanic risk mitigation efforts. However, the complexity of processes prior to an eruption makes the study of the eruption preparatory phase challenging. More specifically, detecting volcanic tremor signals, which could serve as a sign of magma reaching the surface, can be difficult due to the high rate of seismic activities before eruptions. Although the seismicity rate usually increases before eruptions, elevated seismicity could occur without ensuing an eruption as well. In this study, we demonstrate that the clustering of volcanic tremors using deep neural networks trained on single-component spectrograms can reveal the precursory volcanic tremor signals three days before the 2021 Geldingadalir eruption albeit the signal was not directly visible in the seismic waveform. In general, we observe that the clustering results are consistent with the major phases of the eruptive activity ranging from unrest activities, continuous lava extrusion, and different levels of lava fountaining as have been described in previous studies. In particular, the temporal evolution of cluster memberships as a result of the deep embedded clustering supports the interpretation that an increase in discharge rate in late April 2021 led to the shifting of eruption style from vigorous outflow to lava fountaining in early May.

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3-D seismic modeling of "calabash-resonances": Conduit-guided-wave excitation by magma-chamber wavefield capturing

DOI: 10.57757/IUGG23-1971 - LINK

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Numerical simulations of seismic wave propagation in magma-filled conduits, located within the volcanic edifice, have been described in several previous publications. The calculations are usually limited to 2-dimensional vertical cross-sections through the edifice and consider the excitation of seismic waves by events located within the conduit. Under such configurations, the conduit, due to its lower seismic velocities, can act as an efficient wave guide. The effects on the seismic wavefield have been used to explain observations of relatively long-period seismicity observed at several volcanoes. In our numerical study (based on the "Salvus" software package), we perform wavefield calculations for 3-dimensional models of the volcanic edifice and include a magma chamber at the base of the conduit. Furthermore, in contrast to previous studies, we consider wavefield effects due to earthquakes located within and below the edifice, but outside of the conduit. The results show that the magma chamber acts as a trap for the incident wavefield and further redirects it into the conduit. The capturing of the wavefield is more efficient if the magma chamber is relatively large. The multiple reflections of the wavefield from the boundaries of the magma chamber cause long-lasting reverberations which are effectively channeled along the conduit. These "calabash resonances" may be responsible for some of the low-frequency seismic signals observed at volcanoes and can potentially be used to better constrain the geometry of the magmatic plumbing system.

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JV04a - Volcano Seismology (IAVCEI, IASPEI)

Estimating the seismic moment-based magnitude for earthquakes occurring in Mt. Etna volcano area

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The moment magnitude is closely related to the seismic moment, which quantifies the energy released by earthquakes, and is therefore important for understanding volcanic dynamics and assessing seismic hazard.

In this study, we calculate the moment-based magnitude (M_W) for selected seismic data sets, using different approaches in distinct magnitude ranges to cover the widest possible range of magnitude that characterizes Etna's seismicity. Specifically, we computed the M_W from a dataset of full moment tensor solutions of earthquakes that occurred in the magnitude range $3.4 \leq M_L \leq 4.8$ during 2005-2020; we created a dataset of seismic moment and associated M_W for earthquakes $2.0 \leq M_L < 3.4$ obtained by analyzing source spectra; we fine-tuned two relationships, for shallow and deep earthquakes, to obtain M_W from response spectra. Finally, we calibrated a specific relationship between M_W and M_L for the Etna area earthquakes in the range $2.0 \leq M_L \leq 4.8$ and for microseismicity ($M_L < 2.0$) using synthetic data. Our results show that the scaling between M_L and M_W is 1 for magnitude $2.0 \leq M_L \leq 4.8$, while it becomes 2/3 when we extend the relationships to $M_L < 2.0$.

All the empirical relationships obtained in this study can be applied in real-time analysis of the seismicity to provide fast and robust information on the released seismic energy.

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All the empirical relationships obtained in this study can be applied in real-time analysis of the seismicity to provide fast and robust information on the released seismic energy.

JV04a - Volcano Seismology (IAVCEI, IASPEI)

Localised seismicity accompanying eruption cycles at Sierra Negra volcano in the Galápagos Islands, Ecuador

DOI: 10.57757/IUGG23-3959 - LINK

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Large basaltic volcanoes offer natural laboratories to study the fundamental processes of crustal deformation and seismogenesis. High rates of magma flux in to and/or out of shallow reservoirs can result in strain rates and stress regimes that seldom occur in purely tectonic settings. Eruption cycles at Sierra Negra, a basaltic caldera volcano in the western Galápagos Islands, Ecuador, are often associated with particularly high amplitudes and rates of deformation, and high rates of seismicity. Spatiotemporal patterns of surface deformation at Sierra Negra can largely be explained by magma flux in and out of a shallow sill within a laterally continuous viscoelastic medium. However, seismic strain is localized almost exclusively on an intra-caldera ‘trapdoor’ fault system. Here we describe the seismicity and deformation that occurred before, during, and after the 2018 eruption at Sierra Negra, documenting the activation and stress evolution of the trapdoor fault system. During the 13 years and 6.5 m of inflation before the eruption, increasing seismicity rates with both time and total uplift, and progressively degreasing Gutenberg-Richter b-values. The stress conditions on the trapdoor fault reversed during the co-eruptive deflation. On resumption of inflation, the number of earthquakes per unit of uplift was very low, and the b-value high, reflecting the newly relaxed stress state of the fault system.

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JV04a - Volcano Seismology (IAVCEI, IASPEI)

Volcano monitoring and modelling using Distributed Acoustic Sensing (DAS) on a subglacial volcano: Grímsvötn, Iceland

DOI: 10.57757/IUGG23-1385 - LINK

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We present the results of an experiment with Distributed Acoustic Sensing (DAS) on Grímsvötn in Iceland, and the potential of Full Waveform Inversion with DAS.

We deployed a 12 km long fibre-optic cable for one month (May 2021) on Grímsvötn, Iceland's most active volcano, which is covered by the large Vatnajökull glacier. The cable was trenched 50 cm into the ice, following the caldera rim and ending near the central point of the caldera on top of a subglacial lake.

We have discovered previously undetected levels of seismicity using an automated earthquake detection algorithm that is based on image processing techniques. We identified first arrival times with an automated cross-correlation based algorithm, developed specifically for complex and local events recorded with DAS. The first arrival times, combined with a probabilistic interpretation and the Hamiltonian Monte Carlo algorithm, yield event locations, their respective uncertainties, and effective velocities along ray paths, even in the absence of a detailed velocity model. Finally, we complete our initial catalogue with local magnitudes, which reveals nearly 2000 events in total, of which ~1% was detected by the local network. This local microseismicity shows spatio-temporal clusters, with active parts of the caldera fault.

We use this catalogue as a starting point for simulations of the complex environment, with the aim of going towards Full Waveform Inversion with DAS data. We show the current challenges and progress towards inverting the data for both subsurface structures, and source characteristics.

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JV06a - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Thermal and mechanical properties of the Martian soil from InSight HP3 data

DOI: 10.57757/IUGG23-0928 - LINK

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The NASA InSight Lander on Mars includes the Heat Flow and Physical Properties Package HP^3 [1] to *in-situ* measure the surface heat flow. Temperature sensors were to be installed at a target depth of 3–5m by a small penetrator, nicknamed the mole. A radiometer to measure the surface temperature complements the package. The mole, requiring friction on its hull to balance remaining recoil from its hammer mechanism, did not penetrate to the targeted depth. Instead, it reached a depth of 40cm, bringing the mole back-end 2–3cm below the surface. Lessons learned from the penetration failure have been discussed by [2]. The root cause of the failure - as was determined through an almost two years long campaign - was a lack of friction in an unexpectedly thick cohesive near-surface duricrust. The mole was used as a penetrometer and a thermal probe [3,4] instead and the hammering signals were recorded by the InSight seismometer [5]. Accordingly, the soil is highly porous and layered with a density of 1200kg/m^3, thermal conductivity of 39mW/m K, cohesion between 4 and 25kPa, and s and p wave velocities of around 115 and 60m/s, respectively. The thermal conductivity varies with the season and the atmospheric pressure by +/-5% showing that gas in the pores contributes significantly to the heat transport.

[1] Spohn et al. (2018) doi:10.1007/s11214-018-0531-4
[2] Spohn et al. (2022) doi:10.1016/j.asr.2022.02.009
[3] Spohn et al. (2022) doi: 10.1007/s11214-022-00941-z
[4] Grott et al. (2021) doi:10.1029/2019EA000670
[5] Brinkmann et al. (2022) doi:10.1029/2022JE007229

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Comparing Earth, Mars, Venus and Titan in terms of seismic solid/atmosphere coupling and subsurface/atmosphere elastic compliance.

DOI: 10.57757/IUGG23-3089 - LINK

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[3]Jet Propulsion Laboratory/California Institute of Technology, Science and Technology, Pasadena, USA
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On the Earth, with more than a century of seismology and on Mars, with the recent InSight seismic data, seismic signals generated through the coupling of the atmosphere with interior have been detected after atmospheric explosions, either due to coupling near the source or near the seismometer. Subsurface structure inversion have also been made on Mars and on the Earth from the joint recording by seismometer and pressure sensor of subsurface elastic deformation generated by atmospheric vortexes and the subsequent inversion of compliance.
On the opposite, gravito-acoustic signals in the Earth atmosphere have been also detected after earthquakes and tsunamis. While no such signal has been observed on Mars, their detection seems realistic on Venus, either with infrasound sensors in the atmosphere or with ionospheric sensors in orbit.
We present here a short comparative review of observations on Earth and Mars, with focus on coupling near the source due to atmospheric or surface explosion, on the detection at the station of atmospheric signal through compliance and on the subsurface inversion of compliance from atmospheric sources. We then extrapolate to Titan, for which we present synthetics illustrating how seismometer, such as those of the DragonFly mission, could also be used for detecting atmospheric infrasounds through compliance effect.
We finally compare Earth and Mars in terms of seismic atmospheric-interior coupling with two other terrestrial bodies of the solar system, Venus and Titan, here again, we illustrate with synthetics the strength of atmospheric signals generated by quakes and discuss perspectives, in terms of observation strategy.

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JV06a - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Earth – Moon – Mars lithospheric attenuation properties comparison

DOI: 10.57757/IUGG23-3402 - LINK

Sabrina Menina[1], Ludovic Margerin[2], Taïchi Kawamura[1], Gregoire Heller[3], Drilleau Mélanie[4], zongb Xu[1], Marie Calvet[2], Raphael- F Garcia[4], Brigitte knapmeyer-endrun[5], Sebastian Carrasco[5], Keisuke Onodera[6], Philippe Lognonné[1], Alexander Stott[4], William.b Banerdt[7]
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[3]CEA, DAM- Dif, Arpajon, France
[4]Institut Supérieur de l'Aéronautique et de l'Espace, Supaéro, Toulouse, France
[5]Bensberg Observatory, University of Cologne, Bergisch Gladbach, Germany
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[7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

Following its deployment at the surface of Mars, the SEIS seismometer of the NASA-InSight mission recorded tens of high-frequency Martian seismic events (> 1Hz) which we analyzed to characterize the attenuation properties of the Martian lithosphere from an Earth-Moon-Mars comparison perspective. The Martian waveforms are generally depolarized and show P and S arrivals with a gradual beginning, a broad maximum and a very long coda decay. These characteristics are reminiscent of the seismic wavefield in the terrestrial oceanic lithosphere at high frequency (Po and So above 2Hz). To constrain the attenuation properties on Mars, we modeled the energy envelopes of very-high frequency events (>2Hz) using a multiple-scattering approach, in which we considered a stratification of velocity and attenuation in the medium. We found that a simple model composed of a highly scattering crust overlying a weakly inhomogeneous mantle is sufficient to explain the main features of Martian events. We found that the Martian crustal diffusivity (10-12 km^2/s) is similar to the estimation obtained in the lithosphere of the Atlantic Ocean (15–60 km^2/s, Hannemann et al. 2022), but higher than the Lunar crust value (2 km^2/s). The absorption attenuation results indicate that the Martian crust is globally dry (Q_μ^{-1} ~ 10^{-4}) compared to the terrestrial crust (~ 10^{-3}). Our results suggest that the basaltic nature and the heterogeneities of the crust are the main source of the scattering in the Martian and oceanic lithospheres. By contrast, the extreme strength of the scattering on the Moon suggests a predominant role of fractures.

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JV06a - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Review of the seismicity on Mars

DOI: 10.57757/IUGG23-3734 - LINK

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[1]ETH Zurich, Earth Science, Zurich, Switzerland
[2]ETH Zurich, Swiss Seismological Service, Zurich, Switzerland
[3]University of Bristol, Earth Science, Bristol, United Kingdom
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[5]Imperial College, Earth Science, London, United Kingdom
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[7]JPL, Earth Science, Pasadena, USA

The InSight mission collected an astounding seismic dataset from Mars during more than four years of operation until it was retired in 12/2022. The Marsquake Service detected over 1300 seismic events. The largest marsquake reached magnitude 4.6. Two other significant events are distant impacts, with magnitudes M4.0 and 4.2 and crater diameters of 130 and 150 m respectively. We present the current understanding of the Martian seismicity and the different types of events observed on Mars.

Low Frequency (LF) family are the largest events and include energy predominantly below 1 Hz. They are similar to teleseismic events on Earth, with clear P and S waves. The epicenter is known for about half of the LF events, fewer have constrained back-azimuth. Seismicity occurs at only a few spots around Mars - a large number of LF events are located at 26–30° at the volcanic Cerberus Fossae region. Two events lie beyond the core shadow and have PP and SS phases. High-frequency (HF) family exhibit energy predominantly at and above the 2.4 Hz local subsurface resonance. HF events generally have magnitudes below M2.5 and originate from central Cerberus Fossae. Likely these are shallow events associated with volcanic dykes. HF events have inter and intra seasonal trends not yet understood. A small number of HF events have higher frequency content, up to 20–30 Hz with amplification on the horizontal components, and are termed Very High Frequency (VF) events. The closest VF events include a distinctive acoustic signal, and remote imaging confirms they are impacts.

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JV06a - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Seismicity and volcanism on Mars

DOI: 10.57757/IUGG23-3941 - LINK

Simon Stähler[1], Savaş Ceylan[1], John Clinton[2], Domenico Giardini[1], Martin Knapmeyer[3], Anna Mittelholz[4], Clément Perrin[5], Ina Plesa[3], W. Bruce Banerdt[6]
[1]ETH Zurich, Earth Sciences, Zurich, Switzerland
[2]ETH Zurich, Swiss Seismological Service SED, Zurich, Switzerland
[3]DLR, Institute of Planetary Research, Berlin, Germany
[4]Harvard University, Department of Earth and Planetary Sciences, Cambridge MA, USA
[5]Univ. Nantes, Laboratoire de Planétologie et Géodynamique, Nantes, France
[6]California Institute of Technology, Jet Propulsion Laboratory, Pasadena CA, USA

No active volcanism has been ever observed on Mars, but the planet has many recent traces of volcanic activity and significant parts are covered by volcanic units (*1*). The InSight seismic dataset localizes more than half of the observed seismic activity in Cerberus Fossae (*2*), a young (<10 Ma (*3*)) graben structure in Elysium Planitia, previously interpreted as a result of dyke intrusion (*4*) or large-scale tectonic stress (*3*). While initial reports of volcanic tremor (*5*) could not be confirmed, spectral analysis of marsquakes observed in this region show a warm, elastically weakened source region (*6*), e.g. due to partial melting at lithospheric depths (*7*) or deformation due to a mantle plume (*8*). The significant contribution of this small region to Mars' global seismic budget *(9)* means that volcanism shapes the planet's surface at a higher rate than contraction. We discuss the mechanisms of Martian seismicity as they are currently understood and their relation to orbitally observed tectonics.

1. K. L. Tanaka *et al.*, *USGS Geol. Investig.*, 3292–3292 (2014).
2. S. Ceylan *et al. Phys. Earth Planet Inter.* **333**, 106943 (2022).
3. J. Vetterlein, G. P. Roberts, *J. Struct. Geol.***32**, 394–406 (2010).
4. R. Ernst, *et al.*, *Annu. Rev. Earth Planet. Sci.***29**, 489–534 (2001).
5. S. Kedar *et al.*, *JGR Planets*, 126 (4) (2021).
6. S. C. Stähler *et al.*, *Nat. Astron.***6**, 1376–1386 (2022).
7. A.-C. Plesa *et al.*, *Adv. Geophysics*. **63**, 179–230 (2022).
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JV06b - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

The spectral response of silicate glasses: a new resource to decipher chemical characteristics of volcanic products on planetary surfaces.

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[1]University of Perugia, Department of Physics and Geology, Perugia, Italy
[2]INAF-IAPS, Institute for Space Astrophysics and Planetology, Roma, Italy
[3]LESIA-Observatoire de Paris, Université PSL- CNRS- Sorbonne Université- Université de Paris, Paris, Italy
[4]INAF, Astrophysical Observatory of Arcetri, Florence, Italy
[5]ASI-SSDC, Space Science Data Center, Rome, Italy
[6]University of Siena, Department of Physical Sciences- Earth and Environment-, Siena, Italy
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Silicate glasses represent an important component in volcanic products, and since volcanism occurred on all terrestrial planets in the solar system, they might influence the spectral response of portions of planetary sur-faces. However, their spectral characteristics are not always considered for the interpretation of planetary surfaces and terrains, giving their blurred spectral response and the supposed lack of information they can provide.
In this study, we used experimental petrology to produce glassy samples having a wide variety of chemical compositions, and we characterized them by means of reflectance and emissivity in different spectral ranges, to observe the variation of their spectral characteristics with changing chemical composition and with varying granulometric characteristics.
In the Mid-Infrared range, we observed a systematic shift of spectral features, both for reflectance and emissivity spectra, that can be modelled with SiO2 and SiO2 + Al2O3 + TiO2 content, whereas the shape of the spec-tra is determined by a complex interaction of chemical and granulometric characteristics. As for the Visible and Near Infrared spectral range, we observed a correlation between the spectral slope and the iron content and speciation. Our results suggest that accounting for the spectral properties of silicate glasses, when interpreting spectral data obtained from the surface of terrestrial planets, will help in the characterization of magmatic bodies and volcanoclastic materials.Thus, we offer an open-source database of collected spectra within the Space Sci-ence Data Center (SSDC), a facility of the Italian Space Agency (ASI) which includes data processing and data archiving center (www.ssdc.asi.it).

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JV06b - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

A model for the angle of repose of dry cohesive granular materials on planetary surfaces

DOI: 10.57757/IUGG23-4541 - LINK

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The surfaces of Earth, Moon, Mars and many other celestial bodies of our solar system are composed mainly of particulate materials, such as regolith, sand and dust. One of the most important observables characterizing the physics of these materials is the angle of repose, i.e., the angle of maximum stability of inclined granular surfaces such as heaps, crater walls and dune slip faces. However, this angle is affected by still poorly understood grain-scale processes. Attractive particle-particle interactions become more effective than particle weight the smaller the grains are, but the stability of granular landscapes on planetary surfaces has remained elusive. Therefore, a theoretical model for predicting the angle of repose as a function of particle size and gravity would have broad impact in the planetary, environmental and engineering sciences. Here we present such a model, which we have derived from grain-scale simulations under consideration of contact and van der Waals interactions. Our model reproduces quantitatively experimental data of the angle of repose, from gravel and rock particles to dust-sized grains, as well as simulation predictions with gravity from 0.06 to 100 times that of Earth. Based on our model, we present a method for estimating the angle of repose on a given planetary surface by suitably adapting the particle size in the laboratory, without the need for generating extra-terrestrial gravity. We also show how the angle of repose can be used as a proxy for grain attributes and the solid fraction of particulate materials on the surface of celestial bodies.

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JV06b - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Torsional oscillations in Jupiter and their link to tropospheric variability

DOI: 10.57757/IUGG23-1450 - LINK

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Jupiter's weather layer exhibits long-term and quasi-periodic cycles of meteorological activity. There are cycles with intervals from 4 to 9 years, dependent on the latitude, which were detected in 5µm radiation, which provides a window into the cloud-forming regions of the troposphere. However, the origin of these cycles has been a mystery. We propose that magnetic torsional oscillations/waves arising from the dynamo region could modulate the heat transport and hence be responsible for the variability of the tropospheric activity. These axisymmetric waves are magnetohydrodynamic waves influenced by the rapid rotation, which have been detected in Earth's core. Using the Juno magnetic field model, together with the density distribution model, we compute the expected speed of these waves. For the wave excited by variations in the zonal jet flows, their wavelength can be estimated from the width of the alternating jets, yielding waves with a half period of 3-5 years at mid latitudes, consistent with the intervals with the cycles of variability of Jupiter's North Equatorial/Temperate Belt identified in the visible and infrared observations. The nature of these waves is revealed by technique, dynamic mode decomposition, applied to the spatio-temporal data for 5µm emission. Our results imply that exploration of these magnetohydrodynamic waves may provide a new window to the origins of quasi-periodic patterns in Jupiter's tropospheric clouds and to the internal dynamics/dynamo of Jupiter.

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JV06b - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

How to understand volcanic processes on Jupiter's moon Io

DOI: 10.57757/IUGG23-2168 - [LINK]

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Jupiter's large moon Io is intensely tidally heated and is covered by >100 very active volcanic centers (greater than Kilauea's average heat flow). These are high-temperature eruptions that can be monitored remotely, even from Earth-based telescopes. However, there are multiple key questions that can only be answered by a spacecraft mission dedicated to Io: Is the magma dominantly mafic or ultramafic in composition? Are the eruptions sourced directly from the mantle or from shallow magma chambers? What is the role of sulfur and sulfur compounds in the volcanism? What is Io's total heat flow and how does it vary with latitude and longitude? How does the volcanism relate to the tectonics producing >10 km high mountains? What is the distribution of melt in Io's interior? Is there a magma ocean? Is the orbital resonance creating the tidal heat in equilibrium or does it vary periodically? How has Io evolved over time? A spacecraft mission with at least 10 close flybys of Io can address these questions, provided it carries the right science payload including visible cameras designed to measure liquid lava temperatures as well as map the surface topography and monitor activity, thermal-IR cameras sensitive from 1-50 microns, magnetometer and gravity science experiments to understand interior melt and lithospheric thickness, and a mass spectrometer to measure the composition of erupted gases. This is the basic concept of the Io Volcano Observer mission concept, which will be expanded for NASA's New Frontiers mission opportunity, with substantial European collaborations.

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JV06b - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Evaluating the attenuation coefficient of the Moon's shallow subsurface using Lunar Penetration Radar (LPR) data

DOI: 10.57757/IUGG23-4643 - LINK

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In 2019, Chang'E-4 (CE-4) landed on the eastern floor of Von Kármán crater on farside of the Moon. The Yutu-2 rover of CE-4 mission carries a Lunar Penetration Radar (LPR) that is equipped with one transmitting and one receiving dipole antenna for 60 MHz, and one transmitting and two bow-tie receiving antennas for 500 MHz. LPR data acquired onboard the Moon Chang'E 4 mission rover Yutu-2 is used to quantify the attenuation within the regolith-dominated shallow subsurface on the Moon. The signal attenuation is estimated using a recently developed approach, based on the downshift of the centroid-frequency of the transmitted pulse, which is assumed to be a Ricker wavelet. In particular, the intrinsic attenuation, which is described in terms of the medium's loss tangent, is retrieved from the back-scattered signals through a probabilistic inversion approach. In addition, the total energy loss (i.e., the sum of scattering and intrinsic losses), evaluated by the inverse quality factor is obtained from the linear fitting of the time amplitude decay. It is thus possible to separate the total loss to its composing components i.e., absorption and scattering terms. From the results, it appears that the intrinsic attenuation along the track is almost constant, while the total loss presents large variations, that are caused by both subsurface inhomogeneities and scatters. In addition, the average loss tangent and total loss are, and respectively.

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JV06b - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

The role of the solar wind on the composition and formation of terrestrial planets

DOI: 10.57757/IUGG23-3524 - LINK

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The solar wind is a possible source of water and other volatile elements that may solve a puzzle of how did terrestrial planets (within the snow line) get a substantial amount of water during their formation. To understand the possible role of the solar wind, we conducted high-energy proton implantation experiments for olivine, orthopyroxene and quartz, and results were analyzed using nuclear resonance reaction analysis. We also conducted a numerical experiment on hydrogen implantation on small dusts and found that for not much hydrogen is trapped in small dusts whose size is comparable to or less than the mean free path of H in the mineral. Using these results, we conclude: (i) a large amount of H can be implanted into these minerals quickly, (ii) the amount of hydrogen implanted in dusts depends on the dust size with a peak at ~0.1 – 1 micron, and (iii) because the energy of D is ~twice higher than that of H in the solar wind, the D/H ratio of trapped H and D in the dusts will be higher than the D/H of the solar wind. For a plausible dust size in the nebular disk (~1 micron), one can get enough water to make a wet planet quickly (<1000 years). We also studied the nature of change in physical properties of mineral (olivine) by high-energy proton irradiation. Irradiation makes olivine mechanically weak and likely increases the dielectric constant. Possible effects on sticking of dusts will be discussed.

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JV07a - The Architecture of the Lithosphere in Volcanic Regions (IAVCEI, IASPEI, IAGA, ILP)

More mantle, more melt: modeling the mantle-derived causes of heterogeneity in volumetric magmatic flux at arcs

DOI: 10.57757/IUGG23-4482 - LINK

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Estimates of volumetric magmatic flux vary significantly between arc volcanoes, both globally and between volcanoes in a given arc. A recent case study of the Cascades arc suggested that variation in basaltic flux from the mantle causes heterogeneity in surface volcanic flux. The root causes of such variations are poorly known, and could relate to along-arc variations in fluid flux from the subducting oceanic lithosphere, changes in mantle thermal structure or composition, or subduction geometry.

We model the volumetric flux of magma from the mantle using a simplified 3-D box model of a subduction zone to constrain the physical factors that most influence the volume of magma produced in the mantle over time. We evaluate the relative contributions of the extents and styles of melting at subduction zones and of the physical parameters of subduction to volumetric flux in a Monte Carlo calculation.

Our results suggest that the volume of mantle available to melt, the extent of wet (flux) melting, and convergence rate are the most important factors controlling volumetric flux. In cases where calculated volumetric flux closely approximates published estimates of volcanic flux, we predict that melting is not constrained to the mantle directly below volcanic edifices, suggesting that magma supplied to the lithosphere requires lateral transport to "feed" the central edifices of volcanoes.

Results from our model may aid in the interpretation of geochemical features like similarity of primitive magmas at adjacent volcanoes and support the idea that mantle magma supply may be an important control on volcano spacing.

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JV07a - The Architecture of the Lithosphere in Volcanic Regions (IAVCEI, IASPEI, IAGA, ILP)

Decisive role of lithosphere in the evolution of Deccan Traps, India and the "Bushe" conundrum

DOI: 10.57757/IUGG23-1343 - LINK

Tarun Khanna[1]
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In the past, extensive studies were carried out in the peripheral regions of the Western Ghat Escarpment (WGE) to postulate the chemostratigraphy of the Deccan Traps, India. However, there remains a dearth of information in the knowledge of the petrogenesis and chemostratigraphy of the Deccan Traps in the Main Deccan Plateau, east of the WGE. Because the continental flood basalts (CFBs) are produced from voluminous melting of an asthenospheric mantle source, it is often difficult to discern the geochemical signatures sourced from the sub continental lithospheric mantle (SCLM). Interaction and contamination of the asthenospheric melts by the continental crust further adds to the complexity of geochemical fingerprinting of the lithospheric mantle. Recently, the basalt lavas recovered from the deep bore-hole well-cores drilled by CSIR-NGRI in the Koyna-Warna region, south-west Deccan Plateau, have yielded new high precision geochemistry and Nd-Sr isotopic information, elucidating the chemostratigraphy, which illustrates the decisive role of the lithospheric mantle in the genesis and evolution of the Deccan Traps. The trace and rare earth element systematics involving Ba, Ti, Nb, Th, Y, La, Gd and Yb in combination with initial $^{143}Nd/^{144}Nd_{(t=66My)}$ and $^{87}Sr/^{86}Sr_{(t=66My)}$ isotopic compositions of a 50 m thick eruptive phase, discovered at a depth of 100 meters below MSL, provided compelling evidence for the genesis of the Bushe-type lavas exclusively from partial melting of the lithospheric mantle and not from the asthenospheric sourced Reunion plume. This "Bushe" conundrum has far reaching implications for the overall processes of evolution of the Deccan Volcanic Province.

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JV07a - The Architecture of the Lithosphere in Volcanic Regions (IAVCEI, IASPEI, IAGA, ILP)

Evidence of fluid-triggered earthquakes and structural segmentation in the Kumaon-Garhwal Himalaya, India

DOI: 10.57757/IUGG23-0060 - LINK

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Using data from a 60-station network in Kumaon-Garhwal (2017-2022), we discovered a north dipping (2^o) low-velocity zone (10-20% drop in Vp and Vs, 10-15% increase in Vp/Vs) between 10 and 20 km depths that correlated with the main Himalayan thrust (MHT). It is worth noting that the rupture zones of the 1803 M_w7.6 Garhwal, 1991 M_w6.8 Uttarkashi, and 1999 M_w6.5 Chamoli earthquakes are all characterised by low-velocity zones, implying that the earthquakes were triggered by the presence of metamorphic or aqueous fluids within the MHT. Through the Common Conversion Point stacking of radial PRFs, we also detect a double Moho structure beneath the aforementioned rupture zones, which could be accumulating high crustal stresses favouring the moderate to large earthquake occurrences in the region.

Our H-K stacking of radial PRFs, as well as joint inversion of radial PRFs and Rayleigh wave group velocity dispersion, resulted in three NNE-SSW trending transverse crustal blocks with significant mafic crust thinning, which are projected to extend down to the lithosphere-asthenosphere boundary. These three transverse lithospheric characteristics correlate to the northward extension of the Delhi-Haridwar ridge, a presumed tectonic boundary (marked by the intersection zone of rupture zones associated with the 1505 M_w8.2 and 1803 M_w7.6 earthquakes), and the Great Boundary fault, in that order. As a result, we hypothesise that these transverse structures may have segmented the lithosphere (below the MHT) in the Uttarakhand Himalaya, reducing the potential rupture lengths and, as a result, the probability of future large earthquakes ($M \geq 8$) in the region.

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JV07a - The Architecture of the Lithosphere in Volcanic Regions (IAVCEI, IASPEI, IAGA, ILP)

Imaging the deep petrophysical architecture of Toba caldera from seismic data

DOI: 10.57757/IUGG23-0134 - [LINK]

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[3]Università Statale d Milano, Department of Earth Sciences, Milano, Italy

The crustal feeding systems of Toba caldera (Indonesia) remain largely unknown due to (1) the lack of seismic images resolving magmatic sills and fluid reservoirs and (2) our inability to translate seismic parameters into meaningful petrophysical quantities. Using data from available seismic arrays, we obtained thousands of dispersion curves sensitive to both the shallow crust and the upper mantle. The usual seismological approach is to invert them for phase-velocity maps at different periods and transform them into a shear-wave model. This model shows low-velocity sill-like structures at different depths under the northern and central Toba caldera; however, the uncertainty in their interpretation cannot be quantified just by looking at their shape, depths and correlation with surface features.

Therefore, we used a Gibbs energy-minimization solver that computes seismic velocities from phase petrology for the compositions relevant to Toba to forward phase velocities directly. A Bayesian Monte Carlo Markov chain inversion then inverts for temperature, composition, background host rock damage and melt content. As a result, every velocity value from our calculations is petrologically feasible. The results identify the portions of the crust where mafic sills are located, quantitatively defining their melt content, chemical composition, rock damage, temperature and associated uncertainty. Due to the low sensitivity of shear waves to temperature, there are still fundamental challenges in defining the thermal structure of the volcano; yet, seismo-petrological inversions are feasible today within one of the most complex crustal systems, a result few expected to achieve a decade ago.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Expert-based and data-driven gully and cliff erosion feature detection in New Zealand

DOI: 10.57757/IUGG23-0228 - LINK

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Erosion in New Zealand is the result of its landscape, with steep slopes and weak rocks, climate, including high-intensity rainstorms, and its history of land clearing. Improved management of erosion requires better targeting of mitigation measures using data on the spatial distribution and dimensions of erosion features. For this, automated object detection approaches and the increased availability of remote sensing data can be exploited. In this study, we explore expert-based and data-driven object detection approaches to map gully and river cliff features in the Wairoa catchment in Hawke's Bay, New Zealand.
Aerial photographs and terrain derivatives obtained from a LiDAR digital elevation model were used as input data for object detection. Manual delineations of gully and cliff features were used as reference data. A knowledge-based object-based image analysis (OBIA) workflow constituted the expert approach. The integration of expert knowledge facilitated the differentiation of erosion types but resulted in the classification of a high proportion of false positives. The data-driven approach consisted of a region-based convolutional neural network (Mask-RCNN) deep learning (DL) model. The DL model showed good results in the delineation of erosion features and differentiated between gullies and cliffs reasonably well, although not all reference features were detected in the validation areas.
We showed that erosion feature detection can benefit from new data-driven techniques such as DL, however, expert knowledge remains an important aspect in such studies because any mapping task benefits from a certain understanding of erosion processes and the environmental characteristics of the study area.

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although not all reference features were detected in the validation areas. We showed that erosion feature detection can benefit from new data-driven techniques such as DL, however, expert knowledge remains an important aspect in such studies because any mapping task benefits from a certain understanding of erosion processes and the environmental characteristics of the study area.

JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Machine learning algorithms for enhanced surface water detection using an integrated approach with Google Earth Engine

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A variety of surface water indices have been developed in the past to detect and monitor water resources on regional, national to continental scal. Less attention has been given to exploiting surface water resources using machine learning algorithms (MLAs). This work compares surface water detection by MLA with surface water indices. Using high-resolution sentinel-1/2 data in the Google Earh Engine cloud computing system we quantify seven widely established surface water indices. Alternatively, we test various MLAs as an integrated approach for enhanced surface water detection complemented by surrogate spatial information like hydro-meteorological and topographic data as additional predictor variables. We establish four MLAs, namely support vector machine (SVM), random forest (RF), gradient tree boost (GTB), and classification and regression tree (CART). All surface water indices and results of MLAs are evaluated for their capability in surface water detection by an assessment of qualitative and quantitative accuracy indicators, including the producer's accuracy, user's accuracy, overall accuracy, and kappa coefficients. Most surface water indices generally provide very good results with kappa coefficients of more than 0.90. MLA-based assessment of surface water detection is not superior in this regard, but provide further insight to dominating predictor variables, and therefore contribute to an improved process understanding of why and where surface water resources occur.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Evaluating the impact of the 9€-ticket on air quality in Leipzig, Germany, through machine learning algorithms

DOI: 10.57757/IUGG23-4995 - LINK

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To confront inflation and reduce private energy consumption, incentives to use public transport are becoming more common; this is the case of the 9€-ticket implemented in Germany during summer 2022 (June-August), which allowed passengers to commute and travel regionally using a reduced-price monthly ticket. However, there is still a lack of knowledge regarding the environmental impacts of the 9€-ticket, e.g., air quality (AQ) improvements derived from changes in private transport trends.

In this study, we aim to assess the influence of the 9€-ticket on air quality in Leipzig. Long-term (2018-2022) times series of atmospheric pollutants (PM, NOx, NO_2), aerosol concentrations (Black carbon), and meteorological variables have been collected. A random forest machine learning algorithm (RFA) is used for meteorological normalization of air pollution and aerosol data to "discount" the effect of meteorology on AQ. This process allows the robust comparison of the AQ time series from 2022 and normal years (2018-2019).

Preliminary use of the RFA successfully normalized NO_2 mass concentrations for 2018-2019. Slight reductions of 5% and 3% in the average NO_2 concentrations were observed in Summer 2018 and 2019 (compared to spring), respectively. The following steps include the meteorological normalization of 2022 AQ data (in preparation) and further pollutants (PM, NOx, BC). The normalized AQ time series from 2022 and normal years will be compared; the analysis will consider the reductions already observed in 2018-2019 and the school-holidays period effect. Additionally, we will assess traffic volume from permanent counting stations from 2018 to 2022.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Synergy of in-situ and hydrodynamic modelling to develop machine learning strategies for dynamic vertical Reference for Maritime and Offshore Engineering

DOI: 10.57757/IUGG23-3653 - LINK

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Increasing demand for coastal and offshore marine applications calls for accurate forecast of instantaneous sea level, storm surges and better understanding of marine processes. Previously one of the major limitations in accomplishing this has been and incompatible vertical reference datum and access to a method that intelligently integrates and analyzes all the different sources. With respect to linking the different data sources the use a high-resolution geoid now allows the determination of dynamic topography which represents a more accurate term for sea level. Thus this study presents a proposed methodology, that uses machine learning strategies to forecast and better understand the marine dynamics.The methodology proposed shall utilize mathematical, statistical and machine learning strategies (e.g. neural networks and inter-technique solutions) along with various relevant data sources (e.g. marine geoid, tide gauges, hydrodynamic models, satellite altimetry etc.) to forecasts sea level in the absolute sense along with their uncertainties. The results is expected to: (i) forecast dynamic topography, storm surges up to 7 day ahead, (ii) identify and predict oceanographic patterns and processes (currents, eddies, etc.), and (ii) determine realistic under keel clearance. The developed method shall be performed in the study area of the Baltic Sea that has an intense activity of shipping and maritime activities.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Machine learning algorithms for quantitative reservoir rock property estimation

DOI: 10.57757/IUGG23-0533 - [LINK]

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Recently, there has been a surge in the utilization of machine learning algorithms in the field of reservoir characterization studies, reflecting a growing interest in the area. The development and application of novel machine-learning methods are crucial for optimizing production by addressing complex reservoir challenges. Here, an attempt is made to shed light on the application of novel machine learning algorithms to infer permeability, a vital property of reservoir rock. Case examples of a few different reservoir systems will be discussed to critically analyze the performance of machine learning tools and their predictability in petrophysical attribute characterization using wireline log data. Further, parametric sensitivity analysis is conducted to identify the influential predictor variable most relevant for the efficient predictive model. This study aims to benefit readers by highlighting existing gaps in reservoir characterization studies and the potential application of machine learning algorithms for reservoir rock property estimation with much accuracy.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

A new deep learning tool to discriminate earthquakes and quarry blasts in Mainland France

DOI: 10.57757/IUGG23-1872 - LINK

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Accurate seismic hazard assessment requires high quality and complete seismic catalogs. Anthropogenic events such as quarry blasts, rock bursts, explosions can introduce significant errors in statistical analyses, especially in areas with low background seismicity rates such as Mainland France.

The BCSF-Renass, a national service of observation in seismology, characterizes the seismicity of the Mainland France, and makes available to the scientific community its seismic catalog. Until 2012, only natural seismicity was localized but since 2012, other types of events are localized and manually discriminated, in particular quarry blasts, marine explosions (demining operation), induced seismicity.

These last years have seen a huge increase of new seismological stations installed in the Resif-EPOS framework. The main consequence is the location by the BCSF-Renass of many low magnitude events, most are quarry blasts (around half in 2022). The work of the analysts is considerably impacted, firstly by a huge increase of events to be processed and secondly by the difficulty of determining the events' origins with the issue of catalog contamination.

This is why the BCSF-Renass, in early 2022, has developed a Deep Convolutional Neural Network (DCNN) tool to automatically discriminate earthquakes from quarry blasts. The learning step was done on the 3 components seismogram spectra on the year 2021 events. The performances are more than 99% for precision and recall, and take well into account the different regions and geological contexts of France. Moreover, this discrimination also worked well for marine explosions, and allowed us to highlight landslides or rock falls.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Efficient Bayesian inversion of planetary structures based on normal mode analysis using generative neural networks

DOI: 10.57757/IUGG23-3163 - LINK

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Bayesian inversion based on normal modes analysis is an essential approach to understanding the internal structure of the Earth and other planets. While the traditional Markov Chain Monte Carlo (MCMC) method provides a feasible approach to obtain the posterior probability density distributions of model parameters, it demands a considerable amount of forward calculation and is slow in terms of computational efficiency. In order to overcome the limitations of the MCMC method, a new approach to Bayesian inversion using generative neural networks has been proposed in this study, which can deliver outcomes equivalent in accuracy to those of the MCMC method with less sample learning. The study proposed three types of Bayesian inversion neural network models based on popular generative neural networks, including GAN, flow model, and energy model, and evaluated their accuracy and discreteness of inversion results. By using the generative neural network method based on actual lunar normal mode observation data, this study has provided posterior probability density distribution of one-dimensional density and velocity structure parameters of the Moon, along with the optimal parameter values.The results demonstrate the potential of using generative neural networks in Bayesian inversion and provide a new direction for future research in this field.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Increasing frequency of anomalous precipitation events in Japan detected by a deep learning autoencoder

DOI: 10.57757/IUGG23-0513 - LINK

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The frequency of large-scale anomalous precipitation events associated with heavy precipitation has been increasing in Japan. However, it is unclear if the increase is due to anthropogenic warming or internal variability. Also, it is challenging to develop an objective methodology to identify anomalous events because of the large variety of anomalous precipitation cases. In this study, we applied a deep learning technique to objectively detect anomalous precipitation events in Japan for both observations and simulations using high-resolution climate models. The results show that the observed increases in anomalous heavy precipitation events in Western Japan during 1977–2015 were not made only by internal variability but the increases in anthropogenic forcing played an important role. Such events will continue to increase in frequency this century. The increases are attributable to the increasing frequency of tropical cyclones and enhanced frontal rainbands near Japan. These results highlight the mitigation challenge posed by the increasing occurrence of unprecedented precipitation events in the future.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Fusion of gridded satellite and earth-observed daily precipitation data in the United States using tree-based ensemble learning algorithms

DOI: 10.57757/IUGG23-0999 - LINK

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[1]*National Technical University of Athens- School of Rural- Surveying and Geoinformatics Engineering, Department of Topography, Zografou, Greece*

Fusing gridded satellite products and ground-based measurements is regularly made for producing precipitation datasets that: (a) cover large geographical regions with high density; and (b) are more accurate than pure gridded satellite products. Therefore, the respective procedures are commonly referred to as “correction” of satellite products. The same procedures often rely on the application of machine and statistical learning regression algorithms in spatial settings. Regression problems can be solved with high accuracy and low computational cost by applying tree-based ensemble learning algorithms. Despite this, information on which tree-based ensemble learning algorithm to select for the contiguous United States (US) and at the daily time scale was until recently missing from the literature of satellite precipitation product correction. Here, we present the first comparison of tree-based ensemble learning algorithms in this particular context. The algorithms compared are random forests, gradient boosting machines (gbm) and extreme gradient boosting (XGBoost). For the comparison, we extracted and utilized information from the PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) and the IMERG (Integrated Multi-satellitE Retrievals for GPM) gridded datasets. We also extracted and utilized earth-observed precipitation data from the Global Historical Climatology Network daily (GHCNd) database. XGBoost was found to perform better than random forests and gbm, and IMERG was found to be more useful than PERSIANN in the context investigated.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

A multivariate-multistep-ahead forecasting of dynamic topography using convolutional encoder-decoder network in the Baltic Sea

DOI: 10.57757/IUGG23-1664 - LINK

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[2]*Tallinn University of Technology, Department of Cybernetics- School of Science, Tallinn, Estonia*

Sea level forecasting that refers to a realistic and accurate vertical datum has became an important component for a variety of disciplines, particularly in coastal and marine disaster management, engineering and navigation. This is encouraged by recent advances in Artificial Intelligence (AI), especially that of encoder-decoder algorithms e.g. Convolutional Neural Network/ Long short-term memory (CNN/LSTM) that considers the nonlinearity have been used successfully to spatio-temporal forecast marine parameters. On the other hand, geoid-referred sea level or dynamic topography (DT), has the potential to be a beneficial alternative term with increased interpretability when compared to sea level anomaly fields, resulting in better ocean circulation and ocean state estimates. Despite its importance, it has received little attention in the literature thus far. As a result, this study develops a method that forecasts dynamic topography using a CNN/LSTM model in the Baltic Sea for the period 2019–2021, which is also validated using along track satellite altimetry sea level.

The methodology employed utilized a multi-source data-fusion strategy with a multivariate-multistep-ahead (1day, 3d, 5d, 7d ahead) framework to generate a new sea level product. Meteorological parameters such as wind speed, sea level pressure, and sea surface temperature, sea surface salinity, and sea surface height also need to be incorporated. The 1day forecast results show a spatial RMSE accuracy within ±4 cm for most of the Baltic Sea. External validation with along-track satellite altimetry data demonstrate differences between forecasted and SA being within 5 cm. The methodology can be applied to other sea areas.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Snow water equivalent forecasting in Sub-Arctic and Arctic regions with recurrent neural networks

DOI: 10.57757/IUGG23-2856 - LINK

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[2]Geological Survey of Finland, Hydrogeology and Modelling, Kokkola, Finland

Snow water equivalent (SWE) expresses amount of liquid water in the snow pack. This information is crucial in many hydrological models, but the actual measurement of SWE requires a lot of labor demanding manual work. Because these in situ measurements are labor demanding and often scarce, efficient, and accurate, forecasts of SWE are crucial to get reliable estimates from current and future state of the hydrological systems. In this work, we compare two different recurrent neural network (RNN) architectures: long short-term memory (LSTM) and gated recurrent unit (GRU). We show that GRU is as accurate as LSTM, but requires less computation and is thus preferred RNN architecture for SWE forecasting. We optimise the efficiency and accuracy of these RNNs with hyper parameter Bayesian optimisation, and comprehensive data preprocessing. We furthermore improve the accuracy of the forecasts by using time to vector representation of time in the RNN architecture. We also show that the RNNs have great generalisation capabilities in SWE forecast, outperforming the commonly used degree-day physical model in generalisation capabilities and forecast accuracy. All the results are demonstrated with real in situ measurements of SWE from Finland, which were carefully selected to present great variety in natural environments. As the outcome, we propose two models which can be efficiently applied to accurate forecasts of SWE: lightweight and heavy. Lightweight model has 321 trainable parameters in total, and has average NSE of 0.91. Heavy model has 51973 trainable parameters, and average NSE of 0.95.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

Large-scale comparison of ensemble learners for merging satellite and earth-observed precipitation data

DOI: 10.57757/IUGG23-1002 - [LINK]()

Hristos Tyralis[1], Georgia Papacharalampous[1], Anastasios Doulamis[1], Nikolaos Doulamis[1]
[1]National Technical University of Athens,
Department of Topography- School of Rural- Surveying and Geoinformatics Engineering, Zografou, Greece

The accuracy of gridded satellite precipitation products is often improved by using ground-based precipitation measurements, together with machine and statistical learning algorithms. This is typically made in regression settings, where the ground-based measurements are the dependent variable and the gridded satellite data are predictor variables. Comparisons of various single machine and statistical learning algorithms in performing this regression task are regularly conducted in the respective literature. Also notably, some of these comparisons are of large scale, thereby providing generalizable findings. Still, a large-scale comparison of ensemble learners (i.e., methods for combining single machine and statistical learning algorithms towards obtaining further accuracy improvements with respect to selecting the best-performing one among these algorithms), such as simple averaging and stacking, was until recently missing from the same literature. Here, we present the first comparison of this kind in the context of interest.

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JA01 - Posters - Machine Learning in Geo-, Ocean and Space Sciences (IAGA, IAVCEI, IAHS, IASPEI, IAMAS, IAPSO)

HMCLab: Solving Diverse Geophysical Inverse Problems Using (Hamiltonian) Monte Carlo Methods

DOI: 10.57757/IUGG23-4228 - LINK

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[2]University of Genoa, Department of Earth- Environment and Life Sciences, Genova, Italy

The problem of solving nonlinear inverse problems and related uncertainty quantification can be addressed by employing sampling strategies, i.e., Monte Carlo methods. Such approach can avoid linearizations and strives to explore regions of the model space where plausible models are located. Recent interest in such strategy has brought to attention the Hamiltonian Monte Carlo (HMC) method, thanks to its peculiar properties which permit tackling high-dimensional problems exploiting information from the gradient of the posterior probability density function. In this work we show how different geophysical problems can be solved with sampling strategies under a common framework, which facilitates experimenting with algorithms, tuning, forward models, etc.. This has been implemented in a software package named "HMCLab", a numerical laboratory which provides: 1) a set of sampling algorithms, particularly focusing on the HMC method, which can be combined with the 2) set of geophysical forward problems such as wave propagation, gravity and magnetic anomalies modelling, seismic traveltimes, etc. Each of the geophysical problems consists of routines to solve the forward problem and to compute the gradient of a misfit functional with respect to the model parameters. The sampling algorithms can thus be used to solve one of the implemented geophysical problems or combined with a user-provided problem. We show examples of the inverse problems that can be addressed with HMCLab and the kind of information that can be retrieved with a probabilistic (or Bayesian) approach.

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JA02 - Posters - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Evaluation of regional observing networks through Observing System Experiment in Northwest Pacific

DOI: 10.57757/IUGG23-2828 - LINK

Inseong Chang[1], YoungHo Kim[1], Young-Gyu Park[2], Gyundo Pak[2], Hyunkeun Jin[2]
[1]Pukyong National University, Division of Earth Environmental System Science, PUSAN, Korea Republic of
[2]Korea Institute of Ocean Sciences and Technology, Ocean Circulation Research Center, Pusan, Korea Republic of

The National Institute of Fisheries Science(NIFS) and Korea Hydrographic and Oceanographic Agency(KHOA) have been collecting temperature/salinity profile data for the marginal seas around Korea using CTD. NIFS collects data during even months, while KHOA collects data during odd months. According to Chang et al. (2023), assimilating data from the marginal seas around Korea improves the subsurface temperature/salinity structure in the East/Japan Sea, as well as in the Kuroshio–Kuroshio Extension region, by controlling the Kuroshio axis through improved Tsugaru Warm Current. Although they only used data obtained by NIFS on even month, it was shown that the regional observation data have a significant impact on the ocean analysis field in Northwest Pacific. We conducted a sensitivity experiment to quantify the impact of regional observation data for all months on the ocean prediction system by applying Ensemble Optimal Interpolation (EnOI) to Korea Operational Oceanographic System–Ocean Predictability Experiment for Marine environment(KOOS-OPEM), which was developed by Korea Institute of Ocean Science & Technology (KIOST). In this study, we demonstrate the importance of regional observing networks in improving ocean forecast skill by comparing physical properties of each experiment.

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JA02 - Posters - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Observation system simulation experiment for new radio occultation observations using multiple small satellites on Venus

DOI: 10.57757/IUGG23-0221 - LINK

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[1]*Keio University, Research and Education Center for Natural Sciences, Yokohama, Japan*
[2]*Keio University, Department of Physics, Yokohama, Japan*
[3]*NASA Jet Propulsion Laboratory, California Institute of Technology, La Cañada Flintridge, USA*
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[5]*Kyoto Sangyo University, Department of Astrophysics and Atmospheric Science, Kyoto, Japan*
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The radio occultation (RO) observations using multiple small satellites are expected not to be interrupted by a thick global cloud layer at about 48–70 km altitudes, and to enable frequent observations of the global vertical temperature distribution at 40–90 km altitudes. In this study, we focus on a phenomenon peculiar to Venus called “cold collar”, in which the polar region becomes warmer than the surrounding latitudes of 60–80 ° at 65 km altitude, and the Observation System Simulation Experiment (OSSE) is carried out assuming RO observation by satellites to be launched in the future. For the Venus assimilation system, “ALEDAS-V” (AFES LETKF Data Assimilation System for Venus) based on LETKF (Local Ensemble Transform Kalman Filter) is used. For the ensemble forecast, the Venus general circulation model “AFES-Venus” is used. For the pseudo-observation data, we use the temperature output of the IPSL Venus GCM (now called the Venus “Planetary Climate Model; PCM”) which represent ideal cold collar by radiative forcing. The temperature at 40–90 km altitudes corresponding to observation points obtained by orbit calculations is used as pseudo-observation data. As a result, while the experiment without assimilation (free run) cannot reproduce the cold collar at 67 km altitude, the RO OSSE reproduces it.

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JA02 - Posters - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Fundamental research for the reanalysis data of the space weather based on the global MHD simulation

DOI: 10.57757/IUGG23-1484 - LINK

Shigeru Fujita[1], Sin'ya Nakano[2], Akira Kadokura[3], Yoshimasa Tanaka[1], Ryuho Kataoka[3], Aoi Nakamizo[4], Hosokawa Keisuke[5], Satoko Saita[6]
[1]The Research Organization of Information and Systems, The Joint Support-Center for Data Science Research, Tachikawa, Japan
[2]The Research Organization of Information and Systems, The Institute of Statistical Mathematics, Tachikawa, Japan
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[4]National Institute of Information and Communications Technology, Radio Research Institute, Koganei, Japan
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The recent global MHD simulation code (REPPU code by Tanaka [2015]) successfully reproduces even observed phenomena such as the auroral breakup of the substorm. We judge that the simulation code correctly reproduces the physical processes of the magnetosphere and ionosphere from the fact that the phenomenon is reproduced realistically.

REPPU code employs several empirical parameters expressing the non-MHD mechanisms. We tried to determine the optimal values of the parameters by using the data assimilation technique. For this purpose, we improve the REPPU code to include both the effect of the inclined rotation axis of the Earth and the effect of the discrepancy between the rotational axis and the magnetic axis.

Next, we apply the data assimilation technique to determine the ionospheric conductivity distribution which is given as empirical parameters in the original REPPU code. For this purpose, we use the ionospheric electric potential determined by SuperDARN and AE indices. We employed the ensemble variational method as the assimilation technique to obtain the optimal values of the parameters. As a result, we obtained that the ionospheric conductivities are enhanced compared with the empirical results. At the same time, modification of the ionospheric conductivity does not change significantly the magnetosphere. The simulation data become the “reanalysis data” of the space weather which is useful for space weather research. Our future goal is to provide a database of the reanalysis data for space weather.

References

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JA02 - Posters - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

A practically-oriented synthesis of machine learning concepts and algorithms for probabilistic hydrological post-processing and forecasting

DOI: 10.57757/IUGG23-1228 - LINK

Georgia Papacharalampous[1], *Hristos Tyralis*[1]
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The various probabilistic hydrological post-processing and forecasting tasks are receiving growing attention nowadays due to the larger degree of information that the probabilistic predictions and forecasts can offer to the practitioners compared to the best-guess predictions and forecasts. At the same time, several machine learning concepts and algorithms are remarkably relevant to dealing with these important tasks, and a pronounced intensification in the research efforts for benefitting from this specific relevance has recently emerged. This presentation will provide a practically-oriented synthesis of the most relevant machine learning concepts and algorithms for the above-outlined context of interest based on a recent forward-looking review. Key ideas and information that can lead to effective popularizations will be emphasized, as such an emphasis can support successful future implementations and scientific developments. In the same forward-looking direction, open research questions will be identified and ideas to be explored in the future will be proposed.

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JA02 - Posters - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

Developing prediction system for current structures in Yeosu Bay by assimilating Coastal Acoustic Tomography

DOI: 10.57757/IUGG23-2830 - LINK

Na Young Park[1], *Hyemin Lim*[1], *Young Ho Kim*[1]
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The importance of accurate coastal current prediction is becoming increasingly recognized for responding to maritime accidents and improving marine environments. The ocean model can overcome the limitation of an existing current observation, which is usually limited to pointwise or surface measurements, by providing extensive coastal current fields. However, since the model results are constrained not only by the numerical nonlinear problem, but also by the open boundary and initial conditions, it is essential to verify and update them through observational data assimilation.
Coastal Acoustic Tomography(CAT) is a remote sensing method that can infer physical variables such as temperature, salinity, and current by using ocean acoustic propagation speed. CAT is powerful to monitor ocean regions and has been shown to improve an ocean model's ability (*Park and Kaneko*, 2000).
In this study, we developed a data assimilation system to assimilate CAT data into a high-resolution ocean model in Yeosu Bay, Korea. We used the Regional Ocean Modeling System (ROMS) with a horizontal resolution of about 100m, and applied data assimilation of CAT applying the Ensemble Kalman filter(EnKF). We also modified the wind stress flux parameterization by introducing the concept of air stability which is associated with the temperature difference between the ocean surface and 2m atmosphere. This study aims to evaluate the effects of CAT data assimilation and wind stress parameterization.

<Reference>
1. PARK, Jae-Hun; KANEKO, Arata. Assimilation of coastal acoustic tomography data into a barotropic ocean model. Geophysical research letters, 2000, 27.20: 3373-3376.

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JA02 - Posters - Data Assimilation and Statistical Learning in Earth and Space Sciences (IAGA, IACS, IAHS, IAMAS, IASPEI)

The Antarctic continent mapped by global similarity association

DOI: 10.57757/IUGG23-2140 - [LINK]

<u>Tobias Staal</u>[1], Anya M. Reading[1], Matthew J. Cracknell[2], Jörg Ebbing[3], Jacqueline A. Halpin[4], Ian Kelly[1], Emma MacKie[5], Mohamed Sobh[6], Ross Turber[1], Joanne M. Whittaker[4]
[1]University of Tasmania, Physics, Hobart, Australia
[2]University of Tasmania, CODES Earth Science, Hobart, Australia
[3]Kiel University, Department of Geosciences, Kiel, Germany
[4]University of Tasmania, Institute for Marine and Antarctic Studies, Hobart, Australia
[5]University of Florida, Department of Geological Sciences, Gainesville, USA
[6]Leibniz Institute for Applied Geophysics LIAG, Seismic- Gravimetry- and Magnetics section, Hannover, Germany

The geology of Antarctica is formed from cratons, accreted terranes from multiple supercontinental cycles, and ongoing tectonism and glaciation. It would be a mistake to assume that the subglacial continent is geologically less complex than any other part of the world.

Geophysical data and the observed interaction between the solid Earth and the ice sheet suggest several distinct geological regions in the interior. Antarctica's margins have been affiliated with geological observations in adjoint Gondwana neighbours, and those projections identify Antarctica as a hub in the supercontinent cycle rather than a snowbank at the margin of the map. However, producing a robust tectonic map of the interior is challenging, as existing datasets and models are inconsistent and the interpretations ambiguous.

We map the tectonic domains of the Antarctic continent by applying a similarity approach. From multivariate observables in other continents, we calculate the most similar tectonic setting for each location in Antarctica and assign discreet distributions of tectonic classes. Observables include potential field data, seismic tomography, and, where applicable, geological observations. We use information entropy and cost function to optimise and evaluate the robustness of the model. Our results refine and redefine the tectonic map of the interior.

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Impacts of radio occultation data assimilation on landfall and precipitation forecasts of low-predictability atmospheric rivers over the eastern North Pacific

DOI: 10.57757/IUGG23-2082 - LINK

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This study explores the potential impacts of global navigation satellite system radio occultation (RO) data assimilation on the forecast performance of low-predictability atmospheric rivers (ARs) over the eastern North Pacific through a regional model and sensitivity experiments. ARs with large forecast errors of landfall and precipitation in the global operational model are analyzed. To understand the contribution of RO data assimilation on forecast performance, sensitivity experiments are performed for selected AR cases that brought significant precipitation to the western US (stronger or equal to Category 3). Results show that, for weekly forecasts, assimilation of RO data can improve the location of high moisture and low pressure centers, resulting in better forecast performance of AR landfall. For 2-day forecasts, assimilation of RO data can improve the patterns of low-level jet and moisture flux, leading to more accurate precipitation forecasts. Although conventional observations, satellite retrievals, and radiances also have positive contributions to the AR forecasts, RO data can provide higher vertical resolution observations and mainly improve the forecasts of AR structure and precipitation areas.

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JA03 - Posters - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Recovering far-field data for the 1883 eruption of Krakatau

DOI: 10.57757/IUGG23-1345 - LINK

Duncan Agnew[1]
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The January 15 eruption of Hunga volcano in Tonga has provided an unprecedented volume of data on global air-pressure waves and volcanic tsunami. In order to apply the knowledge from these data to the only other example, the eruption of Krakatau (Indonesia) on August 27, 1883, I am assembling an openly accessible digital dataset of both the the air waves and the tsunami from this nineteenth-century example, the first for which any instrumental records (barograms and marigrams) were produced. Its narrow focus and range of sources makes this an unusual data rescue project. The 1888 report produced by the Royal Society of London does not show the air waves in a useful way; the report does contain reproductions of marigrams, though without describing their sources. In a few cases original records survive, but usually what is available is a journal article about some observations, with a foldout plate showing a photolithograph of the original or of a drawing of it. About half of the barograms listed in the 1888 report can be found in some form, and I have found a few new records both of air pressure and sea level; most pressure records come from a wide range of mercury barographs. Images of all records will be used to produce digital time series, relying on custom software. Two results already evident are that many barograms show similar waveforms, which differ from those of the 2022 eruption; and that tsunami were observed across the entire North Pacific ocean.

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JA03 - Posters - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Historical Analog Earthquake Data in Romania

DOI: 10.57757/IUGG23-3561 - [LINK]

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[5]University of Bucharest, Faculty of Physics, Magurele, Romania

The seismicity of Romania is characterized by seismic events with magnitudes between $1 \leq Mw \leq 7.9$ (the largest earthquake produced in Vrancea in 1802) and depths from crustal to intermediate-depth domains. The Vrancea source generates a few significant earthquakes (magnitudes above 7.0) per century. The instrumental period of recording seismic activity in Romania started in 1888 when one of the first seismic stations from Europe was installed in Bucharest, at the Seismic Observatory from Cutitul de Argint. The seismicity recorded before the instrumental period is mostly based on macroseismic observations and early seismic instrumentation. Once the instrumental recording started to operate, over one million paper seismograms had been collected in the National Institute for Earth Physics archive. The archive includes records on smoked and photographic paper and ink recordings since 1900. The analog paper recordings are affected by continuous degradation which is followed by loss of data over time. Since the paper recordings are strongly affected by the passage of time and the storage conditions, currently, work is being done on the inventory of the existing seismograms, their evaluation, and scanning.

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JA03 - Posters - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Evaluation and utilization of historical terrestrial gravimetric data over the Czech Republic territory

DOI: 10.57757/IUGG23-4934 - LINK

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In the presented project, we focus on the digitization and refinement of the terrestrial gravimetric data observed in 1940–1961 period on the territory of the present day Czech Republic. The project aims to utilize most of these older gravimetric observations by correcting and homogenizing them to the modern geodetic reference systems.

All available catalogues and data sources have been collected, digitized, and converted to the relational database. Also metadata are collected and converted to the database too. Besides, we digitized and georeferenced also the original analogue maps or schematic plots documenting the locations of the individual observations. All the digitized gravimetric data have been verified during the process. Data is transformed to modern geodetic reference systems with the aid of the acquired metadata. Finally, by applying geostatistical analysis techniques, data validity has been verified against later, more accurate terrestrial gravimetric data and new gravimetric observations.. As the later observed gravity field is often affected by gravity changes and variations, we need to address all known mass transports, primarily sourced in later anthropogenic interference, as mines, quarries, dam reservoirs, etc.The described process enabled us to significantly improve the reliability, accuracy and georeference of all available terrestrial gravimetric data in the Czech Republic.

The resulting homogenized gravimetric database can be used in any other project demanding accurate knowledge, or even time-differentiated knowledge, of the gravity field over the Czech Republic. Just as a geodetic applications, we can mention a quasigeoid modelling or realization of the normal heights geodetic reference system.

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JA03 - Posters - Analogue Data for the Future: Preservation and Present-Day Utilization of Historical Data in the Geosciences (IAGA, IACS, IASPEI, IAHS, IAG, IAPSO)

Alpine stereographic photographs taken by Baron Roland Eötvös (1848-1919)

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Baron Roland Eötvös (in Hungarian: Eötvös Loránd) as a scientist is known from (1) the Eötvös rule in capillarity, which has of equal importance as the universal gas laws; (2) from the Eötvös balance, by means of which he demonstrated the equivalence of gravitational and inertial masses, with a precision of 10^{-9}; (3) from the field version of his balance, which was the first geophysical field instrument. As a Public Man, he was founder and leader of scientific and sport organizations, a supporter of young talents, a sportsman, among others a mountaineer. In the Dolomites the Eötvös peak is named after him. He captured the landscape by his stereo camera. His photos were digitized on the occasion of the Eötvös 100 Commemorative Year, in two steps: (1) the already known photos in January 2019 (eotvos100.hu/en/page/tomorlatvany_kepek), (2) photos newly found in the Hungarian Museum of Science, Technology and Transport, in 2020 (virtualiskiallitas.kozlekedesimuzeum.hu/s/eotvos/page/dolomitok).

Recognizing the environmental significance of these documents, on the occasion of the 175th anniversary of his birth, we present several three-dimensional photos from this South Tyrol collection, as a part the complete oeuvre of one of the greatest pre-IUGG geoscientists, Baron Roland Eötvös. More photos (and an original Eötvös balance) can be seen in the booth of Institute of Earth Physics and Space Science (Sopron, Hungary), with the financial support of the Eötvös Loránd Research Network.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Evaluation of marine magnetotelluric responses to rugged bathymetry and coast effects simulated by three-dimensional forward modeling

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Marine magnetotelluric (MT) method is used to probe the crust and mantle beneath seafloor in terms of electrical conductivity. Rugged bathymetry and coast lines can distort MT responses significantly, and therefore, it is critical to simulate MT responses by incorporating such structure boundaries into an electrical conductivity model. Recent three-dimensional (3D) MT forward modeling methods can incorporate complex structure boundaries by computationally effective manners. However, it has not been deeply studied how stably or accurately the numerical modeling methods can synthesize the MT responses to practical complex structures. In this study, I propose a simple method to evaluate the random component of the uncertainty of MT forward modeling for 3D conductivity models, which includes rugged bathymetry and coast lines, in a Cartesian coordinate system. The method is based on the idea that the horizontal coordinate system can be selected arbitrarily for a general 3D structure. By synthesizing MT responses to the model in several different coordinate systems, the mean, standard deviation, and coefficient of variation can be calculated. The proposed method was applied to two practical situations of marine MT arrays in the northwestern Pacific and southern Atlantic. The results show that the uncertainty is comparable to real observation errors and is significantly dependent on the MT impedance element, period, site, structure model, and horizontal coordinate system. This method is also useful for testing the appropriate selection of the coordinate system and mesh design.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Characterizing offshore freshened groundwater along the Maltese Islands through geophysical and geochemical data integration

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The rising demand for potable water in densely populated coastal regions has recently promoted growing research interest in detecting offshore freshened groundwater (OFG) worldwide. Recent geophysical studies along the continental margins offshore Israel, New Zealand, Malta, and the United States of America provide some examples of integrating geophysical and borehole data to constrain the spatial extent of OFGs and estimate their pore-water salinity. However, occurrences of OFGs and the interaction between terrestrial, carbonate-hosted groundwater systems with seawater are understudied in many coastal regions by complicated seafloor morphology. In this study, we investigate whether OFG can exist offshore a semi-arid carbonate coastline along the Maltese Islands and explore the possibility of sustainably exploiting these reservoirs as an unconventional source of potable water to relieve freshwater scarcity. We present an integration of 2-D resistivity models derived from marine controlled source electromagnetic (CSEM) measurements with 2-D and 3-D seismic data, core samples, borehole data, and geochemical measurements. Electrical resistivity models identify localized resistive anomalies (> 10 ohm-m) offshore the northeastern coast of Gozo (the second-largest island in the Maltese archipelago). Furthermore, a resistive body is observed at ~ 300 m below sea level close to the coast of Gozo which extends northeastwards and disappears at ~ 8 km offshore. If the anomalous resistive body is associated with pore-water salinity variations or, alternatively, caused by lithological changes, will be discussed through an integrative geological model developed along each profile.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Re-assessing marine geohazards along the Calabrian continental margin in southern Italy

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The Calabrian Arc subduction-rollback system along the convergent Africa/Eurasia plate boundary is among the most active geological structures in the Mediterranean Sea. Single and composite landslides, volcanic features, seismogenic faults, erosive canyons, and fluid flow systems were imaged in this region as part of the recent 2021 Atlas of Marine Geohazards of the Italian Coast, and areas prone to hazards were intially assessed on the basis of their distance from the coast and their morphologiy. The Squillace submarine canyon is one of the most striking features imaged in the Atlas in this region. It is located at only a few hundred meters from the coast and is characterized by dendritic headwalls connected with prominent flash flood river systems onshore.

Here we present the design of new marine geophysical surveys planned for June 2023 within the EU EUROFLEETS+ programme that aims to collect a new multiparameter dataset (MBES and SBP from AUV, aero photogrammetry and sediment samples from ROV) to obtain very high-resolution imaging of the offshore Squillace canyon headwalls and derive lithological and geotechnical parameters indicative of instability, Additionally, we showcase initial work performed within two EU funded PNRR (National Recovery and Resilience Plan) initiatives. Over the coarse of the next three years we aim to generate a new geodatabase of submarine features, including landslides that will enable for example detailed intercompartative assessments of geohazards associated with he Calabrian, Ionian and Tyrrhenian continental margins, and to develop novel approaches for feature recognition based on machine learning and artificial intelligence approaches.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Investigations of Marine Hydrothermal Systems and Seafloor Massive Sulfides with Electromagnetic Methods

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The investigation of marine, hydrothermal systems requires the integration of multi-disciplinary approaches from e.g. biology, geochemistry, geodynamics, mineralogy and geophysics. Scientific research interfaces closely with economic and environmental interests, for which conflicts seem inevitable since exploration and potential exploitation of seafloor massive sulfides may pose a hazard to all biological activity surrounding hydrothermally active systems.

Past investigations have almost exclusively focused on identifying active hydrothermal sites due to the applied technologies: the discovery of sites of interests frequently relied on the detection of temperature or chemical anomalies in the water column, or the identification of characteristic, morphological structures like edifices on the seafloor. In contrast, very little is known about systems where activity has either ceased, is to low to be detected in the water column, or is shielded by sufficiently thick layers of sediment. For such inactive, extinct or buried systems, the use of electromagnetic methods can shed new insights. The sensitivity of electromagnetics towards conductive structures formed by the precipitated minerals is independent of the grade of hydrothermal activity and is able to see through potentially covering sediment layers, thus, providing a valuable constrain to the spatial extents of mineralizations.

At GEOMAR, we have built and applied electromagnetic instrumentation to investigate active and inactive hydrothermal sites in the Mediterranean Sea and at the Mid-Atlantic Ridge. Interpretations in some regions show hidden conductive anomalies in areas without current hydrothermal or relevant biological activity, which could be of interest for research exploration without the potential conflict with environmental sciences.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Shallow water navigation chart in multiple island coastal regions derived from ICESat-2 altimetry and Sentinel-2 imageries

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Although the world's land digital elevation/surface model (DEM/DSM) has been well established through spaceborne and airborne sensors, high-resolution shallow clear water bathymetry remains poorly charted. Knowing the bathymetry in coastal zones is critical, especially for ocean navigation, environmental protection, mineral resources mining, and coastal management. However, surveys of bathymetry data in a traditional way relies heavily on humanpower and cost of equipment/vessels. National Aeronautics and Space Administration's (NASA's) Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), launched in 2018, provides multi-beam georeferenced photon data every 70 centimeter along its ground tracks with a 91-day repeat orbit. The georeferenced photons can be utilized to derive water depth on coastal islands even without any on-site data. Here, we examine a synthesis of ICESat-2 ATL03 photon data and Sentinel-2 optical imagery to derive a bathymetry model based on Beer-Lambert law. Once the model is trained, the prediction of accuracy using goodness-of-fit (GoF) helps to select the most appropriate images. We select multiple islands in the South China Sea as testing sites, where the availability of coastal bathymetry models is scarce because it is costly and difficult to survey. The final bathymetry model is derived with a composite of multiple images, and the bathymetry accuracy via cross validation meets the requirement of category C in Zones of Confidence (ZOC) of the Electronic Navigational Chart (ENC) in 0-15m.

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Measuring tectonic strain build-up on the seafloor with the GeoSEA array

DOI: 10.57757/IUGG23-0247 - LINK

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The GeoSEA array is a network of seafloor transponders used in direct path measurements at water depths up to 6.000 m. Direct path acoustic ranging with baselines up to 2.500 m resolves seafloor deformation at high resolution (< 5mm repeatability). The array is configured for continuous interrogations to monitor the state of seafloor deformation, e.g. at volcanic flanks, active faults or continental slopes. Data retrieval may be conducted via an acoustic modem using a vessel or a surface vehicle (wave glider) as a platform. The GeoSEA array consists of 34 acoustic transponders, which have been deployed in various tectonic settings. One network monitored the stress build up along the North Anatolian Fault offshore Istanbul in the Sea of Marmara, indicating a potential slip deficit of up to 2.5 m. No right-lateral creep was detected, indicating a locked or very moderately creeping fault segment which is currently accumulating strain. Three networks consisting of 8, 10 and 5 transponders, respectively, were installed in 2015 on the continental slope and outer rise of the North Chilean subduction zone and were recovered in 2022. The arrays were positioned in water depths between 2.400 m to 5.200 m using the deep-sea cable of RV SONNE. A further scientific target was the instable eastern flank of Mt Etna volcano in Italy, where up to 6 transponders were installed in 2016 in recurrent campaigns. We provide an overview of the monitoring strategy for these different campaigns and the main results of the direct path ranging.

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Oceanic crustal structure of the Guatemala Basin: Preliminary results from seismic tomography

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From December 2022 to January 2023, a geophysical survey of the RRS JAMES COOK in the Guatemala Basin collected two refraction and wide-angle seismic profiles, each with 11 Ocean-Bottom-Seismometers spaced at ~7.5 km intervals. Both two profiles have excellent data quality and recorded clear crustal refraction (Pg), upper mantle refraction (Pn), and very long-extended Moho reflection (PmP) phases. To utilize the data adequately, we use the layer-stripping top-down method to conduct joint refraction and reflection seismic tomography of these two profiles. The preliminary results show that the crustal thickness beneath line p300 is ~5 km, which is thinner than the global average thickness of the oceanic crust at ~6 km. This is in agreement with the result of down-hole logging and wide-angle seismic survey to the southwest at the ODP site 1256. In contrast, the seismic structure of profile p400, which is located to the northeast of profile p300, reveals ~6–7.5 km thick oceanic crust. Both two profiles present a high velocity gradient of oceanic layer 2 from ~4.5 km/s to ~6.5 km/s and a low velocity gradient of oceanic layer 3 from ~6.5 km/s to 7.2 km/s, which were interpreted as basaltic layer and gabbroic layer, respectively, showing typical oceanic structure. Our data present a very clear Moho reflection and our preliminary analyses suggest the area in the vicinity of line p300 fulfilled the requirements for future Moho drilling and thus may represent a site for the flagship drilling project MoHole of the International Ocean Discovery Program (IODP).

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Japan Coast Guard's GNSS-A seafloor crustal deformation observation and the data strategy

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Around the Japanese Islands, major subduction zones along the plate boundaries of the Pacific Plate and the Philippine Sea Plate have repeatedly caused megathrust earthquakes. GNSS-Acoustic ranging combination technique (GNSS-A) is an effective tool to measure the absolute position on the seafloor, from which we can visualize the plate boundary conditions at these subduction zones. The Japan Coast Guard has been conducting GNSS-A observations at the sites deployed along the Japan Trench and the Nankai Trough, named the Seafloor Geodetic Observation Array (SGO-A).
At the SGO-A sites, we have been periodically conducting campaign observations for approximately 20 years. In these two decades, technological advancements in our observation and analysis techniques have enabled us to detect shallow slow slip events lasting for a year (Yokota and Ishikawa 2020). Our decadal observations have revealed the processes related to the 2011 Tohoku-oki Earthquake (Watanabe et al. 2021). We have also been developing a csv-based data format for GNSS-A observation data, which we have been discussing in a working group of the Inter-commission Committee on Marine Geodesy (ICCM) of the International Association of Geodesy (IAG).

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Seismotectonics of oceanic transform plate boundaries in the Northeast Pacific: Constraints from ocean bottom observation

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Among the recently evolving transform faults, the Blanco transform fault system (BTFS) in the northwest off the coast of Oregon, is strongly segmented and resembles other segmented oceanic transform systems, such as the Siqueiros in the East Pacific Rise, which developed from a pre-existing transform fault that was subjected to several extensional events due to a known shift in spreading direction. However, plate tectonic reconstructions suggested that the BTFS developed from at least two large ridge offsets rather than a single transform fault, emerging from a series of ridge propagation events after the plate reorientation at ~5 Ma.

We investigated the seismotectonic behavior and tectonic evolution of the BTFS using ocean-bottom seismometer data from the Blanco Transform OBS Experiment (2012–2013) as well as high-resolution multibeam bathymetry, aeromagnetic, and gravity datasets. Interestingly, we observed no evidence for the existence of either transform faults or fracture zones around the BTFS before 2 Ma, indicating that there were no pre-existing transform faults before the formation of the BTFS. Therefore, we propose that the BTFS developed from two broad transfer zones rather than pre-existing transform faults. Moreover, local seismicity shows significant along-strike variations, revealing different modes of slip in the eastern and western BTFS. Seismic slip vectors suggest that the western BTFS is an immature transform fault system since its reorganization is still taking place, but the eastern BTFS accommodating the plate motion is mature. The BTFS acts as a natural laboratory to understand the mechanisms controlling the development of oceanic transform plate boundaries.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Improved sea floor topography from sea-surface gravity gradiometry inversion

DOI: 10.57757/IUGG23-1865 - LINK

Lucia Seoane[1], Guillaume Ramillien[2], Didier Rouxel[3], José Darrozes[1], Bastien Plazolles[2], Corinne Salaün[3], Thierry Schmitt[3]
[1]Paul Sabatier University, Géosciences Environnement Toulouse, Toulouse, France
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Besides sea floor topography maps can be estimated by inversion of satellite-based gravity and/or geoid height anomalies, in particular in large oceanic provinces that are uncovered by ship tracks, it has been demonstrated that gravity gradiometry is a powerful technique to retrieve more details of regional bathymetry as gravity tensor is composed by the high frequency of the gravity field. Inversion of vertical gravity gradient data derived from the radar altimetry technique offers the possibility to reach greater resolutions (< 10 km). We propose an efficient approach based on Kalman filter to restore seafloor shape as well as lithospheric parameters, e.g. the crust and elastic thicknesses, for combining different types of geophysical information including mainly GG data. For validation, our estimated maps of bathymetry are confronted to existing data sets in areas well-covered by observation surveys.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Science meets art: What can we see by illuminating the ambient deep sea?

DOI: 10.57757/IUGG23-4478 - LINK

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Visuals like graphs, tables, and charts are frequently used by scientists as a way to communicate their findings or to make them more accessible to the general public. Some information or scientific ideas, however, are complex and challenging to understand. In contrast, art speaks to everyone. Collaborations between science and the arts are becoming more and more crucial in developing fresh strategies for promoting Earth science.
Here we present a current interactive immersive science-art work, concentrating on the deep marine realm where people cannot hear or see. In order to investigate how the deep sea is evolving as well as how mankind is hearing and comprehending the environment that supports us, our work breaks through the background noise of the ocean. The auralization and visualization of submarine seismic data have been the focus of our team's (Deep Sea Light, DSL) effort, and it provides a fantastic opportunity to learn more about the dynamic world of deep oceans. We have effectively detected the activities of earthquakes, volcano eruptions, and even fin whale sounds using seismic stations. We further employ the Audio Spectrum and the Touch Designer to visualize vast soundscapes in 3D perspective and physically convey various settings to the audience via artistic interactive devices. Our effort helps to reveal the ambient deep-sea world and demonstrate how people should listen to and comprehend it via the lens of the ocean soundscape.

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JA04 - Posters - Marine Geodesy and Geophysics – Opportunities & Hazards (IAGA, IAG, IASPEI, IAVCEI)

Accurate bathymetry inversion through combining gravity-geological method and residual neural network: A case study over puerto Rico trench

DOI: 10.57757/IUGG23-4155 - LINK

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The acquisition of accurate bathymetry is a challenging task in Marine Geodesy, especially for the area without sonar sounding data, the ocean gravity field is needed to realize the seabed topography inversion process. The gravity-geological method (GGM) is one of the most classic methods for seabed topography inversion. According to the approximate linear relationship between the seabed topography and the short-wave gravity anomaly, the GGM method constructs the regional bathymetry model. However, the correlation between seabed topography and gravity anomaly are non-lineardue to factors such as the geology of the seafloor.

To address this issue, based on the short-wave gravity anomaly obtained by the GGM method, residuals neural network (ResNet) is used by introducing a variety of prior geophysical attribute data information, such as vertical gradient, magnetic anomaly, and sediment thickness. The non-linear relationship between gravity anomaly and seabed topography is then obtained. In the Puerto Rico test area, the accuracy of the seabed topography over the inspection points is improved by ~10m compared with results using the GGM method.

The seabed topography inversion combined with GGM and neural network will provide a new idea for bathymetric survey based on satellite altimetry, which has high feasibility and important application value.

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JA07 - Posters - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Scaling characteristics in ultra low frequency magnetotelluric signals: Investigating of possible earthquake precursors, northern Algeria

DOI: 10.57757/IUGG23-0117 - LINK

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In the recent decade, earthquake-related electromagnetic phenomena have been considered one of the most promising candidates to achieve short-term earthquake prediction. Magnetotelluric measurements still remain one of the most challenging and debated questions in the scientific community regarding short-term earthquake prediction. Since 2018, a continuous recording magnetotelluric station has been installed at the Medea Observatory (Northern Algeria), whose main role is the assessment of seismo-electromagnetic signals. Using an MTU-A Phoenix system, we measure the five components of the telluric and magnetic fields. Multifractal detrended fluctuation analysis is a powerful method for capturing scaling behavior in non-stationary time series. Using an appropriate instability index, it is possible to identify and quantify deviations from uniform power-law scaling, which suggest the presence of changing dynamics in the system under study. In this context, the calculated scaling instability index β (defined as the range of the local scaling exponents) of magnetotelluric time series (in the frequency range below 1 Hz) were investigated. We considered only those seismic events that satisfy the Dobrovolsky rule ($r=10^{0.43M}$). Several significant scaling behaviors in the magnetotelluric temporal fluctuations were revealed, which could be linked with the occurrence of earthquakes in the northern part of Algeria, such as the 2021 Bejaïa earthquake (M = 6, epicentral distance 235 km) and the 2020 Blida earthquake (M = 4.5, epicentral distance 18 km). These results prove to be powerful for short-term earthquake prediction.

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JA07 - Posters - Interdisciplinary Observations of Pre-Earthquake Processes. The Concept of Lithosphere- Atmosphere- Ionosphere Coupling (IAGA, IASPEI (EMSEV)

Searching for anomalous seismic and geomagnetic patterns before moderate earthquakes occurred in Vrancea Romania

DOI: 10.57757/IUGG23-3489 - LINK

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In this paper we try to identify changes of seismic propagation velocities in time, the seismic energy release and geomagnetic deviations from the normal trend before the occurrence of crustal and intermediate earthquakes from Vrancea zone, and to find the correlation in time between them.

In the crust, velocities change before, during and after earthquakes through several mechanisms related to, for example, fault deformations, pore pressure, changes in stress state and rebound processes. The seismic data used in this study consists in the seismic energy and seismic velocities vp/vs, computed from the seismic bulletins of NIEP, for the stations situated in the earthquake preparation area. Calculations are done automatically by the Phenomenal platform https://ph.infp.ro/seismicity/data. Seismic energy release in Vrancea zone was calculated for intermediate-depth earthquakes with Mw>3. The small earthquakes with Mw<3 were taken as background seismicity that releases almost constant the stress. The seismic energy was represented as a daily sum using a logarithmical scale. Then, the cumulative energy released during each identified anomaly was calculated and compared with the anomaly magnitude measured. The Geomagnetic data were taken from Muntele Rosu (MLR) Seismological Observatory of NIEP, situated inside Vrancea seismogenic zone as primary station, and from Surlari (SUA) Geomagnetic Observatory of Intermagnet, as remote station, unaffected by medium size earthquake preparedness processes. Geomagnetic indices taken from GFZ (https://www.gfz-potsdam.de/kp-index) were used to separate the global magnetic variation from possible local seismo-electromagnetic anomalies, that might appear in a seismic area like Vrancea zone.

Work funded by SOL4RISC Nucleu and AFROS Projects
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JA08 - Posters - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Ionospheric effects of the M7.8 and M7.5 Turkey-Syria Earthquake Sequence on February 6, 2023

DOI: 10.57757/IUGG23-3369 - LINK

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[9]Leibniz-Institute of Atmospheric Physics, Leibniz-Institute of Atmospheric Physics, Kühlungsborn, Germany

On February 6, around 01:17 UTC, a magnitude 7.8 earthquake struck south-central Turkey near the Turkey/Syria border. Several aftershocks were registered in the following days, with the largest being a 7.5 magnitude earthquake that struck about 90 km north on the same day around 10:24 UTC.

This paper presents the ionospheric effects detected by ionosonde and GNSS networks covering the Mediterranean area and Europe, with the goal of trying to discriminate the different sources of perturbations affecting the ionosphere and to characterize the different ionospheric wave-like perturbations induced by the earthquake.

Specifically, earthquakes are responsible for different kinds of atmospheric perturbations, depending on the distance from the epicentre. In the near-field, acoustic-gravity waves are generated directly on-site by the strike-slip East Anatolian fault's movement. In the far field, upward propagating acoustic waves induced by surface Rayleigh Waves dominate the ionospheric response. Thanks to the multi-instrument approach, both mechanisms can be distinguished. In particular, thanks to the measurements nature, ionosondes are highly sensitive to acoustic waves, defined by small wavelengths and periods. On the other hand, GNSS-derived Total Electron Content is more suited for detecting waves defined by larger periods and longer wavelengths, such as the ones generated directly by the fault movement. The first results show a clear pattern of the ionospheric disturbances on the ionograms recorded at different distances from the epicentre propagating at a few km/s compatible with the hypothesis of Rayleigh waves related perturbations.

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JA08 - Posters - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Audio-frequency magnetotelluric investigations of the 2018 phreatic eruption site at Mt. Motoshirane, Central Japan

DOI: 10.57757/IUGG23-3992 - [LINK]

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[1]Tokyo Institute of Technology, School of Science, Meguro-ku, Japan
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Phreatic eruptions are one of the eruption styles that are difficult to forecast and occasionally cause significant damage. Understanding the mechanisms of phreatic eruption is essential for minimizing damage. Mt. Motoshirane, one of the pyroclastic cones of the Kusatsu-Shirane Volcano located in central Japan, experienced a phreatic eruption in 2018 that resulted in casualties. The eruption was abrupt with no precursory phenomena. Mt. Motoshirane has been dormant for the last 1500 years, so it has been poorly monitored and studied. Studies conducted after the eruption suggested that the migration of hydrothermal fluids triggered the eruption, but those studies lacked information on shallow subsurface structure. In this paper, we report on the three-dimensional resistivity structure around the craters of the 2018 eruption, which was estimated from the audio-frequency magnetotelluric data obtained in 2020 and 2022. The inferred resistivity structure basically has a two-layer structure composed of a high-resistivity layer corresponding to the Quaternary lavas near the surface and low resistivities corresponding to the altered Neogene lavas below. Shallow moderately high resistivity regions in the low-resistivity layer are considered fluid reservoirs that have become infiltrated as a result of the eruption. Regions around the crack associated with the eruption showed relatively high resistivity, implying that the low resistivity zone is decoupled beneath the eruption site. We will discuss how the phreatic eruption occurred based on these interpretations in the presentation.

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JA08 - Posters - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

The shallow hydrothermal system of Mt. Usu imaged by electromagnetic survey

DOI: 10.57757/IUGG23-3004 - LINK

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We conducted electromagnetic survey at Mt. Usu, one of the active volcanoes in Hokkaido, northern Japan. We succeeded in the first three-dimensional imaging of the resistivity structure beneath the summit crater field of the volcano. This study revealed the geometrical relationship between the subsurface structure and the sources of micro-earthquakes, remagnetization, and ground deformation.

Mt. Usu is an active volcano that has repeatedly erupted about every 30 years since the 20th century. It is known from historical and geological records that the summit crater experienced repeated magmatic to phreatomagmatic eruptions in the past. Even in the present inter-eruptive period following the 2000 phreatomagmatic event on the western flank, remarkable ground deformation, micro-seismicity, and magnetic field changes have been observed in the summit crater field. Therefore, such geophysical monitoring is vital for evaluating the volcano's activity level. On the other hand, although several electromagnetic surveys (e.g., Matsushima et al., 2001) were previously conducted in the past, detailed three-dimensional imaging has been awaited. To this end, we conducted audio-frequency band magnetotelluric surveys in 2021 and 2022 to unveil the shallow three-dimensional electrical structure. Our model recognizes a low resistivity anomaly (1-10 Ωm) extending westward from the Ginuma crater at approximately 200-500 m below sea level. Current micro-seismicity and continuous remagnetization (Hashimoto, 2022) occur slightly above this low resistivity anomaly. On the other hand, the center of the long-term ground deflation (Wang and Aoki, 2019) is located on another low resistivity patch on the northeast side of the crater field.

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JA08 - Posters - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Modelling and inversion of electromagnetic data in volcanic regions – The effect of topography

DOI: 10.57757/IUGG23-2398 - LINK

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Unravelling the internal structure of volcanoes is an essential step to understand the architecture of the magmatic system and advance hazard assessment. Electromagnetic (EM) measurements are particularly suited for this task due to the high contrast in resistivity between melts and solid rock. Due to this, EM surveys of active volcanoes have gained significant attention in recent years. However, many modelling and inversion algorithms only provide a rough approximation of the significant topography of the volcanoes. Currently it is not clear to which level the topography has to be incorporated to provide reliable and robust results. We use two modern finite-element modelling algorithms for magnetotelluric data to assess the impact of different approximations. Based on the geometry of a recent survey at Mt. St Helens we will compare the results of the two algorithms with different topography approximations. We will discuss different strategies for incorporating topography and how to ensure valid calculations of magnetotelluric forward responses.

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JA08 - Posters - Ground and Satellite Electromagnetic Observations Related to Earthquakes, Tsunami's and Volcanic Activity (IAGA, IASPEI (EMSEV), IAVCEI)

Piezomagnetic fields associated with a dislocation source in a layered elastic medium

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The piezomagnetic effect is defined as a change in magnetization with applied stress. Changes in the geomagnetic field caused by the piezomagnetic effect, referred to as the piezomagnetic field, have been theoretically estimated and compared by previous studies to interpret observed variations in the geomagnetic field. However, the piezomagnetic field estimated in previous studies may not provide an accurate estimation because they ignored spatial variations in elasticity, leading to only a rough approximation of the properties of Earth's crust. In the present study, a semi-analytical procedure for calculating the piezomagnetic field arising from a point dislocation source embedded in a layered elastic medium is derived. Following a well-established method of the vector surface harmonic expansion, all of the governing equations written in partial differential equations in a real domain, together with the linear constitutive law of the piezomagnetic effect, are converted to a set of ordinary differential equations in a wavenumber domain. Equations in the wavenumber domain are solved analytically, and each component of the piezomagnetic field in the real domain is obtained after applying the Hankel transform. By using the derived procedure, the piezomagnetic and displacement fields due to a finite fault with strike-slip, dip-slip, and tensile-opening mechanisms are estimated for media with layered elasticity structures. In the presentation, I will also talk about an application to the calculation of the temporal variations of the piezomagnetic field, which will be essential when compared with the actual changes in the geomagnetic field just after the onset of earthquakes.

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JC06 - Posters - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

The formation of a circular collapse crater at Rhonegletscher (Switzerland)

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The formation of circular collapse craters are frequently observed on many receding tongues of formerly active glaciers. In absence of substantial ice flow dynamics, subglacial cavities formed by meltwater conduits are no longer closed down but continuously enlarge. A local depression will form at the surface due to creep with decreasing roof thickness. This process is accompanied by the formation of circular crevasses. Complete loss of stability eventually will lead to the collapse of the entire surface leaving a crater in the ice behind. Understanding the physical processes and conditions governing the collapse crater dynamics is essential to assess processes of rapid glacier retreat and hazards resulting from snout collapses and sudden blockage of subglacial drainage pathways.
On the glacier tongue of Rhonegletscher such an evolution was detected in spring 2022. A monitoring was carried out between June and October in bi-weekly to monthly intervals with drone surveys to document the surface topography, survey of network of ice flow markers and GPR surveys to estimate cavity size. After a successful drilling through the roof, direct measurements of roof thickness and cavity height were conducted in the evolving cavity. Preliminary ice flow modelling results show strain patterns that coincide with the observed low-angle circular crevasses. Although initiated by the presence of a subglacial drainage conduit, our results suggest the mechanical failure of ice lamellas from the cavity roof as main driver of the collapse crater, and subglacial melting by air flow or water drainage as minor influence.

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JC06 - Posters - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Triggering and runout conditions of two rock slope failures in the French Alps: Vallon d'Étache and Crête des Grangettes

DOI: 10.57757/IUGG23-1906 - [LINK]

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In high mountains environments, permafrost degradation causes rockwall instabilities, sometimes leading to rock slope failures. These processes could be a threat for human lives and activities, it is therefore essential to improve our knowledge about their triggering and propagation mechanisms.

This study focuses on two rock slope failures which occured in the *Vallon d'Étache* (Maurienne Valley, France) and the *Crête des Grangettes* (Écrins massif, France) in 2020. These events have respectively volumes around 270 000 m^3 and 35 000 m^3. In both cases, ice in the rockfall scars suggests the presence of permafrost, but its local distribution and its role in the triggering of the events remain to be confirmed. The aims of this study are (i) to assess thermal conditions in which both events were triggered and (ii) to model their propagation. To do so, we first propose a method that combines rockwalls temperature monitoring, statistical modelling of permafrost distribution, geophysical surveys (Electrical Resistivity Tomography) and laboratory measurements (petrophysical model) to explain the thermal conditions under which the rockfalls occurred. Then, 3D models acquired by photogrammetry are used to obtain high-resolution DEMs in order to measure their volumes, and to provide consistent inputs for runout modelling.

This multi-method approach allows to understand the context and the processes leading to rockfall triggering of two events in the French Alps. We also propose depth-averaged flow simulations to model the runout characteristics of the *Vallon d'Étache* rock slope failure.

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JC06 - Posters - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

A machine-learning approach for estimating the snow avalanche danger level and avalanche activity

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Snow avalanche danger level and avalanche activity are key metrics for describing the prevailing hazard situation of mountainous areas during winter. Avalanche warning services publish avalanche bulletins, which include the regional avalanche danger levels and descriptions of the snow cover properties. Physically-based snow cover models calculate the detailed stratigraphy of the snowpack using meteorological variables as input.

In this study the output of a snow cover model is used as input for machine learning algorithms to determine the local avalanche danger level and the avalanche activity at a ski resort. The avalanche activity is characterized by observations of avalanche releases by explosions or by snow groomers.

Two machine learning approaches using the modeled snow stratigraphy and meteorological variables were applied. An artificial neural network was designed to process the snow stratigraphy with convolutional layers and to treat the meteorological time series with recurrent layers. Support vector machines with radial basis functions as kernel functions were used for each output variable. The model results differ, but no model can be specified as best for all cases. This suggests the use of ensemble methodology. Logistic regressions handle ensemble learning and improve final outcomes.

The precision of the model reaches up to 0.73 for the local avalanche danger level, 0.75 for the artificial releases by explosives, and 0.94 for the artificial releases by snow groomers. The temporal evolution of the probabilities of the avalanche danger level provides additional information, which can be relevant for the operational work of the avalanche warning services.

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JC06 - Posters - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Slope instability and permafrost variations at Askja caldera (Iceland) investigated over 50 years with multi-sensor aerial and satellite data

DOI: 10.57757/IUGG23-1813 - LINK

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The morphology of Askja caldera walls demonstrates features related to slope instability and permafrost variations that can be linked to each other. However, the causal link between mass wasting and cryosphere in active volcanic environments is poorly understood. Factors of permafrost degradation and associated slope instability at Askja may involve volcanic heat flow and atmospheric temperature increase. To investigate long-term morphological changes related to slope processes and permafrost activity, we performed photogrammetric processing and comparative analysis of archive aerial, recent Pleiades satellite, and drone data. We extracted DEMs and orthophotographs covering the period of 1970-2022 and revealed evidence of slope instability, previous mass wasting occurring on different scales, and permafrost degradation. The high-resolution multitemporal data allowed recognition of such surface features as emerging tensile cracks and multiple thermokarst sinkholes. Our photogrammetric dataset was complemented with SAR and infrared data processing, and historical ground-based photographs analysis. Our results show that landslides are common at Askja caldera, and considering the identified morphological features, a new mass wasting event can occur at any time. We outline unstable areas at the caldera walls and discuss the relevance of permafrost and instability that may have contributed to the Askja 2014 rockslide avalanche. We suggest that slope instability at Askja poses significant hazards and requires constant remote sensing and on-site monitoring.

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JC06 - Posters - Mountain Cryosphere Hazards (IACS, IAVCEI, IASPEI)

Glacial Lake Inventory of Kinnaur District, Himachal Pradesh, India derived from Landsat Images

DOI: 10.57757/IUGG23-3790 - LINK

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Climate change and associated glacier recession have led to the formation of new glacial lakes and the expansion of existing lakes across the Himalayas. Such lakes pose a potential glacial lake outburst floods (GLOFs) threat to downstream communities and infrastructure. The accelerated growth of glacial lakes has resulted in increased hazard and damage potential of GLOFs in Kinnaur district, Himachal Pradesh. To understand the spatiotemporal dynamism, a temporal inventory of glacial lakes in the study area for the years 2000, 2010, and 2022 is prepared at 30m resolution using Landsat satellite imagery. The study performed a three-step semi-automatic method for mapping glacial lakes based on geospatial techniques that included the use of the normalized difference water index (NDWI), elimination of mountain shadows using the Cartosat digital elevation model (DEM), and manual vectorization of lakes using Google Earth imagery. A total of 147 glacial lakes were identified having an area > 0.25 ha for the year 2022. This study presents an important database of glacial lakes and provides a basis for long-term monitoring and evaluation of outburst flood disasters primarily caused by glacial lakes in the study area.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Simulation of the Antarctic Ice Sheet over last glacial cycle with the coupled solid Earth – ice sheet model PISM-VILMA

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The Antarctic Ice Sheet is the largest but also the most uncertain potential contributor to future sea level rise. Understanding involved feedback mechanisms require physically-based models. Confidence in future projections can be improved by models that reproduce past ice sheet changes and present change rates. The complex interaction between ice, bedrock and sea level plays an important role for the stability of marine ice sheets with characteristic response time scales varying regionally between years and thousands of years due to the heterogeneous Earth structure underneath Antarctica and the interacting ice sheet dynamics.

We have coupled the VIscoelastic Lithosphere and MAntle model (VILMA) to the Parallel Ice Sheet Model (PISM v2.0, www.pism.io) and have run simulations over the last two glacial cycles. In this framework, VILMA considers both, viscoelastic deformations of the solid Earth by considering a three-dimensional mantle-viscosity distribution and a gravitationally self-consistent mass redistribution in the ocean by solving for the sea-level equation. PISM solves for the stress balance for a changing bed topography, which can be updated with coupling intervals up to 1 year in view of fast changes in ice sheet flow and grounding line dynamics.

Here, we show results of coupled PISM-VILMA simulations scored against a database of geological constraints around Antarctica (AntICE2), including sea level index points and GPS uplift rates. We discuss the implications of a three-dimensional Earth structure over one-dimensional profiles for Antarctic ice sheet changes. This project is part of the German Climate Modeling Initiative PalMod.

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30-year surface elevation changes over ice sheets of Greenland and Antarctica from multiple satellite radar altimeters

DOI: 10.57757/IUGG23-1617 - LINK

Baojun Zhang[1], Zemin Wang[1], Jiachun An[1], Mingliang Liu[1], Hong Geng[2]
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[2]Wuhan University, School of Resource and Environmental Sciences, Wuhan, China

As the result of changes in ice dynamics and weather-driven changes on the surface, surface elevation changes over ice sheets are sensitive to climate forcing. Thus, long-term surface elevation changes over ice sheets of Greenland and Antarctica are of essential to assess the impact of climate change. Here, a dataset of monthly surface elevation time series over ice sheets of Greenland and Antarctica at 5km grid resolution using ERS-1, ERS-2, Envisat, and CryoSat-2 radar altimeter observations from August 1991 to December 2020. An updated plane-fitting least-squares regression strategy and Empirical orthogonal function (EOF) reconstruction were applied to ensure the accuracy and self-consistency of the merged elevation time series in the data processing. In addition, the cross-comparison with the IceBridge airborne laser altimeter observations confirmed that our merged dataset is reliable. Benefiting from its high temporal and spatial resolutions, the evolution processes on multiple temporal (up to 30 years) of ice loss from the main outflow glaciers in Greenland and Antarctica can be derived in detail. The spatiotemporal patterns of accelerating or decelerating surface elevation changes over ice sheet related to ENSO (for the Antarctic Ice sheet) and NAO (for the Greenland Ice sheet) indicated that climate forcing shifts oceanic forcing or atmospheric forcing in some way to affect ice sheet changes. Our merged time series provide a vital dataset for exploring the processes of climate forcing driving ice sheet change.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Approaches to constraining East Antarctic rheology using seismic measurements from isolated stations

DOI: 10.57757/IUGG23-0769 - LINK

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It is becoming apparent that the East Antarctic Ice Sheet may be more vulnerable to changing climate than previously thought. Tomographic studies have revealed significant lateral variations in mantle viscosity across Antarctica, which can strongly influence the results of glacial isostatic adjustment models. Glacial isostatic adjustment is an important consideration in sea-level and ice-sheet studies, necessitating improved constraints on rheology in East Antarctica.

Detailed studies of 3D rheology in East Antarctica are challenging due to the sparsity of seismic stations across this region. Stochastic Bayesian approaches to inversion naturally provide information on uncertainties and can be a powerful technique when data is sparse. The utility of such approaches has been demonstrated by the recent results of the Mars InSight mission, in which ensemble model approaches were used to invert for the seismic structure of Mars using recordings from a single seismic station.

We employ stochastic Bayesian approaches recently used on Mars to constrain the rheology of the lithosphere and asthenosphere in East Antarctica. These techniques will be used to develop new methodologies that can be used on data recorded at isolated stations to constrain possible bounds for rheology on a regional scale. In future work, seismic measurements may be used in combination with other techniques such as magnetotelluric measurements to provide additional constraints on solid Earth rheology.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Coupling cryosphere, hydrology, sea-level and solid-Earth processes within the ice sheet and sea-level system model

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Determining the multidecadal evolution of ice sheets and the associated sea-level change informs major decisions for coastal hazard mitigation and societal development at the global scale. Such systems involve physical processes occurring within and between ice sheets, terrestrial water, oceans, and the solid Earth. Important feedback loops have been identified in marine-terminating ice sheets between thickness change near the grounding line and the bedrock response.

We present a new framework for the Ice Sheet and Sea-level system Model that aims at coupling ice dynamics, hydrology, sea level, and solid-earth deformation. This framework features dynamic interactions between processes with support for multiscale resolution. For example, we are able to capture grounding line dynamics in West Antarctica at a kilometric and biweekly resolution, while global sea level is simultaneously computed on yearly timescales. This is achieved by combining spatial partitioning of physical processes, anisotropic meshing, subelemental geometry tracking, and an asynchronous mass transport approach.

Our solid-Earth model is based on high-degree (~10^4) love numbers and is able to account for viscoelastic response in the lithosphere and mantle to surface loading and rotational feedback. Rheology models supported include the Hookean, Maxwell, Burgers, and Extended Burgers models.

Our framework is fully parallelized and optimized to support ensemble modeling for uncertainty quantification purposes. Intended applications include the modeling of ice sheet retreat, sea-level projections, high-resolution coastline migration, Glacial Isostatic Adjustment, and hydrology fingerprints. These will affect the interpretation of numerous geodetic datasets, such as GRACE-FO, GPS, NISAR, ICESat-2, and SWOT.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Pliocene shorelines and deformation of passive margins: A target dataset for dynamic topography models

DOI: 10.57757/IUGG23-4707 - LINK

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[3]Imperial College London, Department of Earth Science & Engineering, London, USA
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Global mean sea level during the mid-Pliocene Epoch, when CO_2 and temperatures were above those of the present day, was significantly higher as a result of reduced global ice sheet coverage. However, the extent to which ice sheets responded to Pliocene warmth remains in question, owing to high levels of uncertainty in proxy-based sea-level reconstructions and solid Earth dynamic models that have been compared with only a limited set of data constraints. Here, we present a global dataset of 11 wavecut scarps that formed over successive Pliocene sea-level oscillations and occur today at elevations varying from ~6 to 109 m above sea level. The present-day elevations of these features have been identified using a combination of high-resolution digital elevation models and field mapping. Using the MATLAB interface, TerraceM, we project the cliff and platform surfaces to determine the elevation of the scarp toe, which often is buried under meters of talus. We correct the scarp elevations for glacial isostatic adjustment and find that this process alone cannot explain observed differences in paleoshoreline elevations. We next calculate the signal associated with mantle dynamic topography by back-advecting the present-day three-dimensional buoyancy structure of the mantle and calculating the difference in radial surface stresses over the last 3 Myr using the convection code ASPECT. We include a wide range of present-day mantle structures (temperature and viscosity) constrained by seismic tomography models, geodynamic observations, and laboratory experiments. Finally, we explore to what extent models can reproduce the different shoreline observations and deformation along them.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Degree dependence of Antarctic GIA correction for GRACE data

DOI: 10.57757/IUGG23-3943 - LINK

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Ongoing mass changes in the Antarctic ice sheet have been observed as gravity changes by the Gravity Recovery and Climate Experiment (GRACE) satellites. The gravity signal also includes the component of the solid Earth's response to surface mass change (Glacial Isostatic Adjustment, GIA). Therefore, estimates of the ice mass change from GRACE data require subtraction of the gravity rates predicted by the GIA model (GIA correction). Previous studies imply that the long-wavelength components dominate the Antarctic GIA correction. To further understand the long-wavelength contributions, we compute the degree amplitude of Antarctic GIA correction in the spherical harmonic expansion. The degree dependence of Antarctic GIA correction is examined here using some typical ice history models. The Antarctic GIA corrections converge by degrees ~ 30 regardless of the choice of ice history models. When the GIA model includes Northern Hemisphere ice history, the degree amplitudes for degrees < 10 vary significantly at each degree. The degree-2 GIA component, due to the influence of the Northern Hemisphere ice history, accounts for 30% or more of the total Antarctic GIA correction. It will be necessary to pay attention to the treatment of the degree-2 component.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Using paleo sea-level data and GIA models to reveal vertical land motion signal: Implications for local sea-level projections

DOI: 10.57757/IUGG23-0544 - LINK

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Vertical land motion (VLM) is an important component in relative sea-level (RSL) projections, while VLM is difficult to derive because of a lack of long-term instrumental records. Geological data offer an alternative, comparing RSL data with glacial isostatic adjustment (GIA) models to isolate VLM.

Here, we present a case study from the Oka estuary, northern Spain. We compare two GIA models (ICE-6G_C and ANU-ICE) with late Holocene RSL data along the Atlantic coast of Europe, showing good fit (misfit < 1.5) at all regions except the Oka estuary (misfit > 4.5), which indicates local subsidence. The nearby GPS (station SOPU, > 15 years) shows a VLM rate of -0.96 ±0.57 mm/yr (subsiding). The VLM rate of SOPU accounts for misfits between GIA models and RSL data, decreasing by ~90% from > 4.5 to ~0.5 after the subsidence correction of RSL data. The VLM rate incorporated in IPCC AR6 projections in Oka estuary is ~0.18 mm/yr (uplifting), which is contradictory in direction. Therefore, the projected sea-level rate is underestimated by 14 - 20% by 2050 and 9 - 26% by 2100 under the five Shared Socioeconomic Pathway (SSP) scenarios.

The sea-level projections of Spanish authorities were based on IPCC AR5. Under RCP4.5 scenario, the future RSL in Oka estuary will increase 0.38 m by 2081-2100, which is underestimated by ~71% (0.65 m) compared with the IPCC AR6 under the SSP2-4.5 scenario by 2100 after correction for local VLM. Our study indicates the importance of local VLM component in projections.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Holocene rapid ice melting and present-day crustal deformation due to GIA around the Lützow-Holm Bay, East Antarctica

DOI: 10.57757/IUGG23-1488 - LINK

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The deformation of the Earth's crust in Antarctica caused by Glacial Isostatic Adjustment (GIA) is highly dependent on the melting history of ice and the viscoelastic properties of the mantle. However, geodetic observations, including Global Navigation Satellite System (GNSS) measurements, are essential in constraining GIA model parameters.

The Japanese Antarctic Research Expedition has conducted GNSS observations and absolute gravity measurements for over 20 years along the coast of Lützow-Holm Bay in East Antarctica, mainly at Syowa Station. This study aims to examine the geodetic signals associated with GIA from the observations made along the coast of Lützow-Holm Bay. Furthermore, the study involves numerical simulations of the signals based on the recently reported rapid ice thinning in this region during the mid-Holocene (Kawamata et al., 2020, QSR).

According to Kawamata's paper, the target region underwent a rapid ice thinning of over 400 m from about 9 to 6 ka, as evidenced by geomorphological surveys and surface exposure ages. The representative deglaciation models, such as ICE-6G, do not incorporate this rapid thinning process. Therefore, the study examines the variability of the geodetic signals using the ice history, including rapid thinning. The predictions indicate that the modified ice history produces consistent results with the observations, thus supporting the occurrence of rapid ice melting during the Holocene. The results also suggest that geodetic observations can aid in constraining the ice sheet melting process in this region. Additionally, the study presents a similar analysis of gravity variations obtained from absolute gravity measurements at Syowa Station.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Three-dimensional velocity variations due to ice mass changes in Greenland – Insights from a compressible glacial isostatic adjustment model

DOI: 10.57757/IUGG23-0512 - [LINK]

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[2]Newcastle University, School of Civil Engineering and Geosciences, Newcastle upon Tyne, United Kingdom
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Glacial isostatic adjustment (GIA) models provide estimates for velocity, gravity and sea-level change based on ice loading scenarios of past glaciations. The input to GIA models is quite extensive and consists of ice histories and a variety of Earth model parameters that describe the three-dimensional (3D) structure and rheology. Here, we will show the effect of a range of lithospheric thickness models on vertical and horizontal velocities in Greenland using a 3D compressible GIA Earth model.
The lithospheric thickness beneath and around Greenland varies from a few tens of kilometres in offshore regions to several tens of kilometres (up to 200 – 250 km) in land areas. However, to date, no one has done an analysis of the impact of lateral lithospheric variation on the 3D velocity field for Greenland as horizontal velocities from incompressible GIA models, which are commonly used, are not suitable to be used due to the neglect of material parameter changes related to the dilatation. Compressible GIA models in turn can provide more accurate estimates of the horizontal and vertical viscoelastic deformations induced by ice-mass changes. We use various lithosphere models as input into a new 3D compressible GIA model code, which is constructed with the finite-element software *Abaqus.* We apply recent ice history models Huy3 and GLAC-GR2a for Greenland in combination with a Little Ice Age deglaciation model. The modelled 3D velocity field is compared against independent GNSS (Global Navigation Satellite System) observations as well as to previously modelled estimates using incompressible 3D GIA models.

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JG01 - Posters - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI)

Ice sheet – solid earth feedback during the last glacial cycle in Antarctica and Greenland

DOI: 10.57757/IUGG23-3121 - [LINK]

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The solid earth influences ice sheet dynamics by controlling bedrock deformation and hence surface elevation and grounding line position. These in turn determine surface and basal melt. Ice-sheet models typically include models to compute bedrock deformation with a constant mantle viscosity (or similar parameter), whereas mantle viscosity can vary strongly underneath the ice sheets. Here we use a recently developed model that couples an ice-sheet model (ANICE) to a finite-element based GIA model that includes 3D variations in viscosity derived from seismic measurements. We investigate the effect of mantle viscosity variations on the evolution of the last glacial ice sheets in Antarctica and Greenland.

In Antarctica, the main feedback mechanism is the effect of bedrock elevation on local sea level and grounding line position. In particular, uplifting bedrock in marine ice sheets reduces ice sheet loss during deglaciation. Results show a grounding line position that is 500 km more outwards when including 3D variations in mantle viscosity compared to a homogeneous viscosity. In Greenland, the main feedback is the effect of bedrock elevation on the surface elevation and hence surface melt. We show that this feedback mainly manifests in north-west Greenland where the mantle viscosity is above average. The higher mantle viscosity leads to higher ice sheet elevation at last glacial maximum, which leads to less surface melt during deglaciation. The results underline the importance of including 3D viscosity in modeling ice sheet evolution.

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JG07 - Posters - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Analysis of 20-year terrestrial gravity and ground deformation changes collected at Mt. Etna: Comparison with satellite data

DOI: 10.57757/IUGG23-4301 - LINK

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[2]*National Board for Technical and Scientific Research, National Board for Technical and Scientific Research, Rosario, Argentina*
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[4]*Istituto Nazionale di Geofisica e Vulcanologia- Italy, Sez. Catania, Catania, Italy*

We present a preliminary comparison between satellite and terrestrial gravity and GNSS data collected in a twenty-year period (2002-2022) at Mt. Etna volcano, with the aim of investigating the capabilities of this integrated approach to study the dynamics of volcanic phenomena over time-scales of months to years.

The terrestrial gravity data were collected through absolute and relative spring gravimeters in the framework of almost monthly campaigns. Instead, GNSS measurements are continuously collected for monitoring purposes.

Regarding satellite data, we used the Gravity Recovery and Climate Experiment (GRACE) data and GRACE Follow-On L3 solutions, that can provide high-quality information about mass distribution at regional and global scales in a long-term interval.

After being corrected for the known effects, reduced terrestrial gravity and GNSS height variations were compared with satellite data. The comparison reveals long-term correlations between the analyzed time series which could represent volcano-scale variations.

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JG07 - Posters - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Geological characteristics of Surtsey volcanic island studied with a gravity survey

DOI: 10.57757/IUGG23-4525 - [LINK]

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Shallow ocean/emergent basaltic phreatomagmatic volcanism observed on November 14, 1963 on the south-eastern end of the Vestmannaeyjar archipelago and the volcanic island of Surtsey appeared on the next day. Surtsey island is the only remaining subaerial part of the constructs from the 1963-1967 eruptions, has two tuff cones in its northern sector while the southern sector is a lava field mostly built on a lava delta. The SUSTAIN drilling in 2017 revealed the existence of an underlying diatreme, giving the island some of the characteristics of a maar volcano. Gravity data obtained on Surtsey in 2014 with a gravity station spacing of 100 m. Density measurements were obtained for surface samples of seafloor sedimentary rock bombs, and lava, tuff and tephra. With the best measured density value for gravity data correction, we use forward modeling to study the vent and surface lava characteristics by considering the four geological units defined for the island: tuffs above sea level, tuffs below sea level, lavas above sea level and a lava delta below sea level, composed of breccias over which lava advanced during the effusive eruption. The boundaries between the bodies defined from the eruption history and mapping done during the eruption. The data reveal low density of the vent areas within the lavas, best explained by cavities within the very shallow magma conduits. However, the small size of the island precludes accurate determination of the dimensions of the deeper diatremes, formed by excavation of the pre-eruption sea floor, through gravity data models.

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JG07 - Posters - Modern Gravimetric Techniques for Geosciences (IAG, IAVCEI, IAPSO, IASPEI)

Scientific assessment of the CARIOQA-PMP quantum accelerometer pathfinder

DOI: 10.57757/IUGG23-4073 - LINK

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Satellite gravimetry is a unique tool to monitor the Earth's mass variations. Satellite missions like GRACE and GRACE Follow-On provide insights into the time-variable gravity field on a global scale to further improve our understanding of climate change processes and geophysical phenomena on scales of a few hundreds of kilometres. The users of gravity field products, however, require higher accuracies and a better spatial and/or temporal resolution, which are not met yet. The current GRACE-FO mission is not only limited by its observational geometry but also by limitations of current instruments, like electrostatic accelerometers. These challenges are partly tackled by current ESA and NASA initiatives to realise satellite gravimetry missions with overlapping mission lifetimes at different orbits. The sensor issue is addressed by the Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometer – Pathfinder Mission Preparation (CARIOQA-PMP) project. The main goal of CARIOQA-PMP is the preparation of a pathfinder mission with view to demonstrating an atom-quantum accelerometer in space within this decade and to realise a technological and programmatic roadmap for a quantum space gravimetry mission meeting user demands from a wide range of applications.

This presentation will give an overview of the scientific activities within CARIOQA-PMP. These include the definition of the quantum pathfinder mission concept, the development of tools to simulate the quantum accelerometer and to estimate its performance, and to evaluate current end-user requirements, including the development of mission designs addressing these needs.

CARIOQA-PMP is funded by the European Union.

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CARIOQA-PMP is funded by the European Union.

JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Managing and sharing volcanological data at the INGV - Osservatorio Etneo

DOI: 10.57757/IUGG23-1516 - LINK

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The study of volcanic activity requires monitoring a variety of data sources, including volcanological, geophysical, and geochemical data. With numerous research organizations and observatories collecting vast amounts of data from sensor networks, it's crucial to have a systematic way of organizing and sharing this information for volcano research and monitoring. This is where the INGV Osservatorio Etneo's TSDSystem framework comes in.TSDSystem is a framework that enables the acquisition and standardization of time series data from different sources within a relational database, and provides synchronized data visualization. The framework is integrated with the OEDataRep web data repository, which is based on the InvenioRDM research data management platform and follows an open access model.The proposed architecture of the system includes various features and services, such as a database optimized for time series data, a RESTful web service based on microservices pattern, near real-time data visualization through modern web technologies, data policy management, and an early warning module. These features help to efficiently manage and share time series data in a timely and accessible manner.

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Data Terra, the French research e-infrastructure for Earth system and environment

DOI: 10.57757/IUGG23-3458 - LINK

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[1]Institut de Recherche pour le Développement, Data Terra, Montpellier, France
[2]Institut des Sciences de la Terre UMR 5275, Data Terra - ForM@Ter, Grenoble, France
[3]IFREMER, Data Terra - ODATIS, Brest, France
[4]Centre National d'Etudes Spatiales, Data Terra - AERIS, Toulouse, France
[5]Laboratoire Image Ville Environnement UMR7362, Data Terra - THEIA, Strasbourg, France
[6]Institut de Physique du Globe UAR3454, Data Terra - ForM@Ter, Paris, France
[7]Environnements et Paléoenvironnements Océaniques et Continentaux UMR5805, Data Terra - ODATIS, Bordeaux, France
[8]Laboratoire Atmosphères Observations Spatiales UMR8190, Data Terra - AERIS, Paris, France
[9]Institut de Recherche pour le Développement, Data Terra - THEIA, Montpellier, France
[10]Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg / CNRS, Strasbourg, France

Data Terra's main mission is to develop a structure for accessing and processing data, data-products and services geared towards observing, understanding and predicting in an integrated manner the history, mechanisms and evolution of the Earth system in response to global changes and extreme events.
Data Terra federates four data and services hubs dedicated to the four physical compartments of the Earth System: Aeris for the atmosphere, Odatis for the oceans, Theia for land surfaces and ForM@Ter for the solid Earth. While aimed chiefly at the scientific community, the unique research e-infrastructure also serves public and socio-economic stakeholders and its multi-source data are accessible via coherent, one-stop portals.

As a digital infrastructure in the field of earth and environmental science, Data Terra works closely with Earth-observation research infrastructures and space agencies. It is backed by a continuum of distributed and interconnected platforms, proposing services that span the full data cycle from access from repositories to value-added processing, thus enabling inter- and trans-disciplinarity studies as well as exploitation of large volumes of data. At national, European and international levels (EOSC Pillar, Fair impact, Phidias, Copernicus services, …), it is advancing the development of open science, implementation of FAIR approaches, contributing to space missions and applications and to the initiative to generate digital twins of the Earth.

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Ensuring ISMN's permanent service for delivering long-term, in situ soil moisture data

DOI: 10.57757/IUGG23-4474 - LINK

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[3]International Center for Water Resources and Global Change ICWRGC, International Soil Moisture Network ISMN, Koblenz, Germany

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[7]Telespazio UK, for European Space Agency ESA ESA-ESRIN, Frascati, Italy

[8]Serco Italia S.p.A., for European Space Agency ESA ESA-ESRIN, Frascati, Italy

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[10]International Center for Water Resources and Global Change ICWRGC, German Federal Institute of Hydrology, Koblenz, Austria

Soil moisture is recognized as an Essential Climate Variable (ECV) because it is crucial for assessing water availability for plants and hence food production. Having long time series of freely available soil moisture data with global coverage enables scientists, farmers and decision makers to detect trends, assess the impacts of climate change, and develop adaptation strategies.

The collection, harmonization and archiving of in situ soil moisture data was the motivation to establish the International Soil Moisture Network (ISMN) at TU Wien, with the financial support of the European Space Agency (ESA), in 2009 as a community effort. The ISMN became an essential source for validating and improving global satellite products, and climate, land surface, and hydrological models. In 2021 permanent funding for the ISMN operations was secured through the German Government (Ministry of Digital and Transport).

The transfer of the ISMN to its new host, i.e., the International Centre for Water Resources and Global Change (ICWRGC)/German Federal Institute of Hydrology (BfG), took place during 2021/2022. Finally, the ISMN started serving data from its new host in December 2022 while keeping the service continuously running throughout the migration. In parallel the team in Vienna developed and launched a new dataviewer. This presentation aims at showcasing new ISMN features as well as recent data contributions as well as next evolution of the ISMN based on synergies and science outcome of the Research and Development activities performed by

ESA in the context of the Fiducial Reference Measurements for Soil Moisture (FRM4SM) project.

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

The Davos Dataset: An (un)fair backstory

DOI: 10.57757/IUGG23-4511 - LINK

Mathias Bavay[1], *Charles Fierz*[1]
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The open data and FAIR data principles have seen widespread adoption in recent years. Unfortunately, the implementation of this vision often falls short of the original goals: seamless reuse is prevented by the reliance on undocumented and inconsistent file formats as well as the lack of metadata. Truly fulfilling the FAIR data vision requires standardization of the data formats and metadata. The necessary standardization efforts have been done, for example with the Climate and Forecast convention and the Attribute Convention for Data Discovery of the NetCDF ecosystem.

But this is only one part of the solution, the other part being that the published dataset must implement such standards. We present our efforts in publishing a dataset made of data from more than 50 Automatic Weather Stations with data extending over a period of 25 years, contributed by nine institutions. The raw data have been standardized into a common format with a common set of parameter names, units and metadata standard. This standardization process is described in a configuration file (one per station) that is used to dynamically generate the final dataset from the raw data.

The challenges in setting up such a dataset have ranged from finding the original data and parsing many different file formats, up to struggling to find the original measurement location or guessing which maintenance operations had been performed a long time ago. Preparing this dataset has therefore taken much longer than originally planned and our hope is that this could be improved in the future.

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Making GeoNet Data FAIRer: lessons learnt from scoring a variety of natural hazard datasets (and how to improve them)

DOI: 10.57757/IUGG23-2199 - LINK

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The GeoNet programme at GNS Science, Aotearoa New Zealand is producer and custodian for datasets used for multi-hazard monitoring, assessment, and research. These datasets are of high national value and significance and range from highly sampled/highly automated to manual and ad-hoc datasets. FAIR is a cornerstone of GeoNet's and GNS Sciences' data principles and an area where we are always seeking to improve.

To understand and demonstrate improvements FAIRness of its datasets, all GeoNet datasets were assessed in 2019. Here we will discuss that scoring effort and the outcomes across our datasets, and show how subsequent targeted work has delivered improvements, using a few key examples:

- Our eruption history database was converted from unstructured document format (GNS report) to a csv format and made fully public; this significantly enhanced its FAIR score across the board.
- Our acoustic/infrasound dataset was made more discoverable by minting a DOI, creating a dataset description record that is based on international web standards and utilising community webservices, leading to significant increases in Findability and Interoperability.

FAIRness scoring is a powerful tool to guide dataset management improvements. It also revealed that some datasets have natural ceilings, particularly when there is a lack of clear international or community standards. More established and cross-peril datasets can achieve high compliance with FAIR data principles with relatively simple steps, while some key improvements generate nary a ripple in the score. FAIRness and open data are key policies for GeoNet, and will remain so for the foreseeable future.

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

New, open socio-hydrological data of paired events of floods and droughts

DOI: 10.57757/IUGG23-2098 - LINK

Heidi Kreibich[1], Kai Schröter[2], Giuliano Di Baldassarre[3], Anne F. Van Loon[4], Philip J. Ward[4]
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[2]Technische Universität Braunschweig,
Leichtweiss Institute for Hydraulic Engineering and Water Resources, Braunschweig, Germany
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A better understanding of the drivers of increasing impact trends is essential for effective flood and drought risk management. However, empirical data is lacking about the processes that result in flood and drought impacts. We present a benchmark dataset containing socio-hydrological data of paired events, which is unique in covering both floods and droughts, in the number of cases assessed, and in the quantity of socio-hydrological data. The advantages of the dataset are that it enables comparative analyses across all the paired events and allows for detailed context- and location-specific assessments. A first analysis of the dataset revealed the general pattern that risk management normally reduces the impacts of floods and droughts, but faces difficulties in reducing the impacts of unprecedented events of a magnitude not experienced before (Kreibich et al. 2022a). The dataset can be used by the scientific community for exploratory data analyses and for the development of socio-hydrological models. As such, the dataset can support solving one of the twenty-three unsolved problems in hydrology (Blöschl et al. 2019). The dataset is available to the public through the GFZ Data Services (Kreibich et al. 2022b).

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Blöschl, G. et al. (2019): Twenty-three unsolved problems in hydrology (UPH) – a community perspective. Hydrological Sciences Journal, 64, 10, 1141-1158, https://doi.org/10.1080/02626667.2019.1620507

Kreibich, H. et al. (2022a): The challenge of unprecedented floods and droughts in risk management. Nature, 608, 80-86, https://doi.org/10.1038/s41586-022-04917-5

Kreibich, H. et al. (2022b): Panta Rhei benchmark dataset: socio-hydrological data of paired events of floods and droughts, https://doi.org/10.5880/GFZ.4.4.2022.002

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

CDDIS FAIR Commitment and nasa's year of open science

DOI: 10.57757/IUGG23-4717 - LINK

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[2]Science Systems and Applications, Code 61A, Greenbelt, USA

The Crustal Dynamics Data Information System (CDDIS) is one of twelve NASA Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAAC) and supports the space geodesy and geodynamics community through the International Association of Geodesy (IAG) services. As an EOSDIS DAAC, the CDDIS is required to meet best archival practices including the Findability, Accessibility, Interoperability, and Reuse (FAIR) Guiding Principles for scientific data management and stewardship which ultimately serves data and product providers and users. This poster will introduce some common tools to ensure clarity for users on how these best practices support their efforts and how to utilize and find the tools built to support them. These include ensuring data is findable via the use of Digital Object Identifiers (DOIs) and facilitating discovery using the Earthdata Search API and NASA's Earthdata Search. As the CDDIS continues to grow during NASA's year of open science, the CDDIS will start migrating to the cloud further ensuring clarity and accessibility of data.

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JH01 - Posters - New, Large, and Open Data for the Earth and Environmental Science Community (IAHS, IAPSO, all associations)

Geo-Environmental Monitoring Station(GEMS):A real time monitoring network to evaluate the impact of anthropogenic activity on environmental conditions on urban areas

DOI: 10.57757/IUGG23-3091 - LINK

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Study of the impact of anthropogenic activity on environmental conditions from urban areas is one of the most important issues at a global level. Human activity on urban areas, such as commercial, industrial, transit, scholar and many-others, represents direct impact on the environmental conditions that influence directly on social and health issues. Monitoring and measure of variations on environmental conditions associated to human activity through time and space. In this work, a device was developed for real time monitoring of different geo-environmental conditions for urban areas: Geo Environmental Monitoring Station (GEMS), integrates different low-cost sensors and a web-based real time processing platform, for storage and visualization of the data. GEMS includes atmospheric sensors to measure particulate matter (PM2.5, PM1.0 and PM10), temperature(°C) , atmospheric-pressure and relative-humidity; noise(dB), ultraviolet-radiation, variations on the earth´s magnetic-field. GEMS can measure all those 9 different parameters and send them via Wi-Fi to the platform for real time processing and visualization The data is free and open access via internet. A dense network is installed on Queretaro,Mexico, a small city with up to 1 million habitants, located in central-Mexico, with an intense industrial activity. Up to 100 GEMS are projected to be installed at the end of 2023. With the data collected by the GEMS network, in combination with other parameters, such as micro-seismicity, magnetic-susceptibility, wind direction etc., a model for anthropogenic impact on environmental conditions is established. GEMS network is planned to be a very low-cost permanent monitoring-system, accessible to society, governments and private companies.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

The Diploma in Seismology for high-school teachers a new version

DOI: 10.57757/IUGG23-3679 - [LINK]

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[1]Universidad Nacional Autónoma de México- Instituto de Geofísica, Servicio Sismológico Nacional, Mexico City, Mexico
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The Diploma in Seismology for high-school teachers is a 170-hour course, the first five generations started with examples of what they could offer their students in their classroom. The content seeks to apply some of the learning and concepts of the physics courses in high school through the analysis of the information recorded in seismograms. In addition to the material presented to the participant through an online platform, and during sessions, they worked on an integrating project, which objective is to prepare them for the use of seismographs and their data in their classes and begin scientific research themselves. We have excellent results; teachers learned and promoted to their students about seismology. Now the high school Physics programs include subjects based on seismology.
At the moment, the sixth generation is taking the new version of Diploma we added a new module, civil protection. The Diploma has reached professors of 20 high schools in Mexico City where also a Raspberry Shake has been installed to integrate the "Red Sísmica del Bachillerato" or the High-school seismic network. The participant teachers know how to extract the information from those instruments and they can work with their students. For the next stage we have support from the project DGAPA-PAPIME PE107023 for displaying the data from Raspberry Shakes installed in five high schools. We will install a screen and a bulletin board with information about basic subjects of seismology. The idea is to have profesors involved in the designed and content production of this board.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Brothers Volcano - virtual experience

DOI: 10.57757/IUGG23-0784 - LINK

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Keywords: VR, Social, Education, Virtual Classroom, Science, Exploration, Geology, Volcanology, Oceanography

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Summary:

Brothers Volcano is a social VR experience for all standalone Meta Quest headsets, that allows users to explore a vast 20km² underwater landscape together while learning about geology, geophysics and oceanography.

The 3D terrain is based on real high-resolution scans of Brothers Volcano, located along the Pacific Ring of Fire, offering breathtaking hiking trails, many informative boards & slideshows along the way, and several scenic spots to read related scientific journals.

To help visualize depth below sea level we built the world's current tallest virtual tower on the volcano's summit, and placed inside a pair of magic shoes which enables faster flight, but to get them one must first find 2 missing keys along the educational hiking trails.

Additionally, the multiplayer experience supports synced lecture slides, laser pointers & Superman flying abilities, so anyone can join the marine adventure and zoom around as a fellow tuna fish.

(As a team we would bring 8 VR headsets for poster session demos)

Target Audience: Primary/Secondary/Tertiary Education and General Public

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Learning Goals:

1. To understand the geology and geophysics of an underwater volcano

2. To learn about the oceanography and marine life surrounding an active undersea volcano
3. To explore virtual reality and its potential as a deeply immersive educational tool

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Instructions:

1. To easy install, search ‘Brothers Volcano’ on the App Store within any standalone Meta VR headset (the experience is free)
2. Interactive tutorials and maps are included within (experience times can easily range from 2 minutes to 2 hours)
3. For pictures and/or sideloading visit : https://sidequestvr.com/app/10009/brothers-volcano-virtual-experience

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Keywords: VR, Social, Education, Virtual Classroom, Science, Exploration, Geology, Volcanology, Oceanography

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Summary:

Brothers Volcano is a social VR experience for all standalone Meta Quest headsets, that allows users to explore a vast 20km² underwater landscape together while learning about geology, geophysics and oceanography.

The 3D terrain is based on real high-resolution scans of Brothers Volcano, located along the Pacific Ring of Fire, offering breathtaking hiking trails, many informative boards & slideshows along the way, and several scenic spots to read related scientific journals.

To help visualize depth below sea level we built the world's current tallest virtual tower on the volcano's summit, and placed inside a pair of magic shoes which enables faster flight, but to get them one must first find 2 missing keys along the educational hiking trails.

Additionally, the multiplayer experience supports synced lecture slides, laser pointers & Superman flying abilities, so anyone can join the marine adventure and zoom around as a fellow tuna fish.

(As a team we would bring 8 VR headsets for poster session demos)

Target Audience: Primary/Secondary/Tertiary Education and General Public

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Boosting Space Weather research and applications in Africa: The NORISK project

DOI: 10.57757/IUGG23-3421 - LINK

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[1]Istituto Nazionale di Geofisica e Vulcanologia, Environment, Roma, Italy
[2]Italian Space Agency, Italian Space Agency, Rome, Italy
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[5]Kenyan Space Agency, Kenyan Space Agency, Nairobi, Kenya

It is well-known that among all the longitudinal sector of the low-latitude ionosphere, the African one is the less studied. This is mainly due to the difficulties in installing and managing long-lasting ionospheric observatories and instruments. Moreover, it is difficult for young people to establish a network of collaboration with scientists outside Africa.

Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Italian Space Agency (ASI) established a framework agreement in 2017 on research activities for the study of Sun-Earth relations and development of Space Weather monitoring. In this context, the New Observatory for Real-time Ionospheric Sounding over Kenya (NORISK) project was funded. The general objective of the NORISK project is to make Broglio Space Centre in Malindi (Kenya) a point of reference in Africa and to contribute to the development of the knowledge supporting Space Weather in the Kenyan scientific community. NORISK specifically aims to:

1. a) Design and develop an ionospheric observatory in Kenya.
2. b) Develop models, algorithms and products for monitoring the low-latitude ionosphere in the African sector.
3. c) Train the new generation of experienced researchers and technicians in the field of research and technological development in support of Space Weather.

The paper shows a general overview of the project and the progress about the training activities.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Free of charge transnational access to world-class European Earth Science research facilities: lessons learned from the EXCITE project

DOI: 10.57757/IUGG23-4004 - LINK

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[2]Utrecht University, Earth Science, Utrecht, Netherlands
[3]Ghent University, Geoscience, Ghent, Belgium

Understanding earth materials is critical to foster technological and environmental development, as well as to advance in Earth-science disciplines, like mineral- and rock-physics, as well as material-oriented (bio)geochemistry. EXCITE, a large-scale infrastructure project supported by the European Union's Horizon-2020 program comprising 15 European institutions for electron and X-ray microscopy, enables free-of-charge Trans-National Access (TNA) to high-end microscopy and microanalysis facilities to develop community-driven technological advancements on Earth materials.

The WP5 of EXCITE aims to facilitate mechanisms and procedures to provide TNA to world-class facilities, specifically addressing new, non-expert or early career users worldwide. By definition, TNA involves a researcher conducting science at a research facility located in a country different from the one in which they are working. The EXCITE TNA programme provides access to 24 imaging facilities in 9 countries. Access is provided on a per-call basis, and is granted following a proposal review process. During the first two TNA calls, almost 150 scientific projects have been supported. Two more calls from both academia and industry users will allow access to facilities until April 2024. Analytical techniques and scientific expertise offered include X-ray micro- to nano-tomography, EPMA, FIB-SEM, TEM, as well as SEM-based imaging, element mapping, EBSD, cathodoluminescence and other specialized imaging tools. Our contribution will present the architecture of the EXCITE-TNA programme and outcomes of the user evaluations, which clearly demonstrate the success of Excellence-driven TNA programmes as a strategic asset of the European research scenario, allowing networking and collaboration and favoring education & outreach in geosciences.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Addressing the need for global standards for geochemical data – the OneGeochemistry initiative

DOI: 10.57757/IUGG23-2338 - LINK

Kirsten Elger[1], Rebecca Farrington[2], Dominik C. Hezel[3], Marthe Klöcking[4], Kerstin Lehnert[5], Alexander Prent[2], Geertje ter Maat[6], Lesley Wyborn[7]
[1]GFZ German Research Centre for Geosciences, Library and Information Services, Potsdam, Germany
[2]AuScope Ltd, no, Melbourne, Australia
[3]Goethe-University Frankfurt, Cosmochemistry & Geochemistry, Frankfurt, Germany
[4]Göttingen University, Geoscience Centre- Geochemistry and Isotope Geology Dept., Göttingen, Germany
[5]Columbia University, Lamont-Doherty Earth Observatory, New York, USA
[6]Utrecht University, Department of Earth Sciences, Utrecht, Netherlands
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The acquisition and analysis of geochemical data are pervasive in the Earth, environmental, and planetary sciences, but few of these data are FAIR (Findable, Accessible, Interoperable and Reusable) or ready to be mined for new knowledge using modern computational methods. The need for global standards and best practices for geochemical data is increasingly urgent so that scientists can better share and analyse geochemical data in a global context.

Standard protocols for exchanging geochemical data among distributed data systems, and for making software tools that support the management, publication, and preservation of interoperable geochemical data need to be developed and approved by a global community. Best practices need to be defined for researchers and laboratories to consistently and comprehensively describe samples, data acquisition procedures, and data quality, and these need to be endorsed and promoted.

OneGeochemistry is an international initiative which aims to support the development of data standards for geochemical data and approaches for their technical and organisational governance. Initially an informal network with representatives from AuScope (Australia), GEOROC, NFDI4Earth (Germany), EPOS Multi-scale Laboratories (Europe), EarthChem (US) and the Astromaterials Data System (US), OneGeochemistry is now funded as a use case of the WorldFAIR project (https://worldfair-project.eu/) and recognised as a CODATA Working Group (https://codata.org/initiatives/working-groups/)

Scientific discovery in many fields will benefit from this global geochemical data network: from the study of global climate change, to present and past biogeochemical cycles, to magmatic processes, to the origin and evolution of our solar system.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

ORBYTS project: Predicting storm times with machine learning

DOI: 10.57757/IUGG23-4002 - [LINK]

Kendra Gilmore[1], Vishal Singh[1], Sarah Bentley[1]
[1]Northumbria University, Mathematics- Physics and Electrical Engineering, Newcastle Upon Tyne, United Kingdom

Historically there has been a lack of diversity in STEM subjects, including physics. Often to counteract this many outreach programs try and encourage young people, especially young girls, to pick up sciences. However, often these outreach programs are one-time events.

ORBYTS (Original Research By Young Twinkle Students) goes about this differently. Scientists are paired with local schools to work on a novel, scientific-relevant project over 3 months with weekly 1-1.5h sessions. This way students are introduced to what and how research works by conducting research themselves, thus hopefully solidifying their interest in STEM. To assess this, we ask them at the end of the project to fill out a questionary on how participating in this project impacted their likelihood to keep sciences in upper secondary school and to pursue a STEM-related career.

For this project, the students use machine learning to predict storm times, which is a problem that space weather scientists are trying to solve. Machine learning has proven to be successful in other fields and its use is becoming more frequent in the space weather community.

The students build a random forest on individual stations in the CARISMA magnetometer chain with magnetic field data and solar wind parameters to assess whether there is a geomagnetic storm or not. Each random forest is trained with the storm time list provided by Sandhu et al. 2021 and its performance is evaluated on a selection of unseen data. The different models are then compared to determine the impact of location on the prediction.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

“JIGYASA” for Geoscience: Role of CSIR-NGRI, India

DOI: 10.57757/IUGG23-1407 - LINK

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[1]CSIR-National Geophysical Research Institute, Seismology, HYDERABAD, India

CSIR-National Geophysical Research Institute (CSIR-NGRI; https://www.ngri.res.in), a premium institute of Earth Science research in India is actively involved in the outreach activities under the “JIGYASA” (a Hindi word which means curiosity), a flagship program of CSIR (Council of Scientific and Industrial Research, India). To tap and trigger the innate curiosity of the students and general public about the Earth, CSIR-NGRI conducts various outreach activities to explain about Earth’s evolution, its environment, natural resources and natural hazards etc. CSIR-NGRI welcomes students to visit its state-of-art laboratories and analytical facilities, conducts webinars for students and the general public, distribute booklets in various languages. CSIR-NGRI researchers and students also visit schools / colleges in different parts of India. Through lectures, models, Do-It-Yourself activities, quiz, conducting education camps, and print / electronic media; we spread awareness about rock types, exploration and exploitation of natural resources, phenomena of earthquakes and Tsunami, earthquake risks and precautions, extent and sustainability of groundwater etc. Further, CSIR-NGRI has open-air rock museum, first of its kind in the country, with large number of rock samples from different geological regions to educate students and general public about different types of rocks, their formation and information provided by these rocks. Since the initiation of “JIGYASA” program, CSIR-NGRI reached approximately 25,000 students and the general public through its outreach activities.

CSIR-National Geophysical Research Institute (CSIR-NGRI; https://www.ngri.res.in), a premium institute of Earth Science research in India is actively involved in the outreach activities under the “JIGYASA” (a Hindi word which means curiosity), a flagship program of CSIR (Council of Scientific and Industrial Research, India). To tap and trigger the innate curiosity of the students and general public about the Earth, CSIR-NGRI conducts various outreach activities to explain about Earth’s evolution, its environment, natural resources and natural hazards etc. CSIR-NGRI welcomes students to visit its state-of-art laboratories and analytical facilities, conducts webinars for students and the general public, distribute booklets in various languages. CSIR-NGRI researchers and students also visit schools / colleges in different parts of India. Through lectures, models, Do-It-Yourself activities, quiz, conducting education camps, and print / electronic media; we spread awareness about rock types, exploration and exploitation of natural resources, phenomena of earthquakes and Tsunami, earthquake risks and precautions, extent and sustainability of groundwater etc. Further, CSIR-NGRI has open-air rock museum, first of its kind in the country, with large number of rock samples from different geological regions to educate students and general public about different types of rocks, their formation and information provided by these rocks. Since the initiation of “JIGYASA” program, CSIR-NGRI reached approximately 25,000 students and the general public through its outreach activities.

JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

A study on satellite on-orbit conjunction assessment system by SaaS

DOI: 10.57757/IUGG23-0678 - LINK

Chih Chien Liu[1], *Yi-Shan Li*[2]
[1]*Chung Cheng Institute of Technology- National Defense University, Environmental Information and Engineering, Taoyuan, Taiwan Province of China*
[2]*Chung Cheng Institute of Technology- National Defense University, Environmental Information and Engineering, Taoyuan City, Taiwan Province of China*

Countries around the world are rapidly developing large number of Low Earth Orbit (LEO) projects which increase the number of satellites in the LEOs. Currently, there are still more than 14,000 man-made space objects and more than 35,000 space debris larger than 10 cm orbiting in orbit. Those space objects and debris will greatly increase the probability of satellite close approach or collision event now and future. This study established a Cloud On-Orbit Conjunction Assessment (COOCA) system, which analysis the short-term potential risk of collision events by a SaaS (Software as a Service). The system ingested the TLE data which is public provided by the 18th Space Defense Squadron of the U.S. Space Force. The Simplified General Perturbations (SGP4), earth gravity parameters and the simplified atmospheric model are adopted to determine the LEO positions and velocity. Then, the collision probability of the potential risk events can be estimated. The results of this research can analyze satellite collision probability by the operators in the satellite ground control center. In addition, general users (especially for students) can learn geodesy theory, geographic coordinate system, time system and Kepler orbital celestial mechanics through the intuitive website platform and automatic process in this COOCA system. It can contribute to the promotion of geoscience education and space science education.

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Let's fire the passion for Geoscience! New geo-comic trilogy.

DOI: 10.57757/IUGG23-3469 - [LINK]

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Dynamics of orogens and rock deformation, Prague, Czech Republic
[2]freelance, xx, Prague, Czech Republic
[3]Institute of Geophysics of the Czech Academy of Science,
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[4]Institute of Atmospheric Physics of the Czech Academy of Science,
Department of Space Physics, Prague, Czech Republic

Communication of geosciences to the general public and students often runs into a lack of understanding of the fundamental processes of the inner Earth. We attempted to bring basic principles of Earth dynamics in an accessible way by creating three short comic books and board games. The structure of the Earth and earthquake mechanism is presented in the comic “When the Earth Quakes”. Origin and manifestation of the Earth’s magnetic field are introduced in the comic book “When the Earth Flares Up” and the danger and beauty of the volcano eruption is shown in the book “When the Earth melts”.

Our approach follows two basic strategies: i) the comics should not tell everything with a lot of explanatory text, but rather try to provoke the reader to look for additional information and it should give the readers some answers and hence start the passion for geoscience; ii) We believe that collaboration between artists and researchers needs to be founded on the equality of their views, discussions, and collective effort. The artists should be given creative freedom and the researchers should explain how the processes work inside the Earth rather than to try to push forward their views of artistic expression of them.

The creation of the trilogy has been funded by the Czech Academy of Science with the contribution of small donors on social media. Thus we decided to make the result of our work publicly available and publish it under the Creative Commons license: https://www.ig.cas.cz/en/comics/.

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International Training Courses on „Seismology, Seismic Hazard Assessment and Risk Mitigation“

DOI: 10.57757/IUGG23-2629 - LINK

Claus Milkereit[1], *Torsten Dahm*[1], *Simone Cesca*[1], *Fabrice Cotton*[2], *Dino Bindi*[2], *Angelo Strollo*[3], *Frederik Tilmann*[3], *Training Course Participants*[4]
[1]*GFZ German Research Centre for Geosciences, 2.1 Physics of Earthquakes and Volcanoes, Potsdam, Germany*
[2]*GFZ German Research Centre for Geosciences, 2.6 Seismic Hazard and Risk Dynamics, Potsdam, Germany*
[3]*GFZ German Research Centre for Geosciences, 2.4 Seismology, Potsdam, Germany*
[4]*GFZ German Research Centre for Geosciences, International Training Course ITC 2023, Potsdam, Germany*

The GFZ organizes annually International Training Courses on “Seismology, Seismic Data Analysis, Hazard Assessment and Risk Mitigation”. They provide theoretical fundamentals and practical training for geo-scientists and engineers from countries in Asia, Africa, and Latin America. The courses are being supported by the German Federal Foreign Office and are a contribution to the global UN Sendai Framework for Disaster Risk Reduction (UNDRR).

In line with the growing demand by participants in former courses for mainly practice-oriented training and workshop discussions related to case studies, the course program comprises, besides introductory and state-of-the-art review lectures on the various subjects of earthquake seismology and risk assessment, extensive practical exercises, demonstrations, workshop discussions and scientific excursions. Generally, the course program aims at developing interdisciplinary problem understanding, acquaintance with the theoretical fundamentals and basic features of modern instrumentation, commonly used models and algorithms as well as developing practical skills in data evaluation and analysis. The courses are being announced through the GFZ website, the EMSC, and IRIS as well as printed information. Additional ad-hoc sponsors are mainly from the hosting institutions and governments in case of regional courses in Asia, Africa, or Latin America.

Since 1992 these 4-week courses are held alternately as world-wide open courses in Potsdam or as regional courses in earthquake-prone countries in Asia, Africa, or Latin America (2006 Kyrgyzstan, 2008 Costa Rica, 2010 Turkey, 2012 Morocco, 2014 Colombia, 2016 Myanmar, and 2018 Ghana). Many of the former course participants became project partner in ongoing research projects of German and European institutions.

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Skills needed in work life: case study of Geoinformatics Master's program

DOI: 10.57757/IUGG23-3209 - [LINK]

Maaria Nordman[1,2], Pinja Lindgren[1], Miina Rautiainen[1]
[1]Aalto University, School of Engineering, Espoo, Finland
[2]Finnish Geospatial research Insitute, Geodesy and Geodynamics, Espoo, Finland

What are the skills that we are teaching in our Master's program in Geoinformatics? How useful those skills are for the new graduates and which skills do they end up using in their working life? What are the skills that the companies that are hiring the new graduates are looking for?

As part of renewing our Master's program we asked our alumni which skills they have found useful in the working life. We also asked a group of our stakeholders to evaluate the same skills for the people they might be hiring. We had a set of predefined skills, both general and field-specific, that we asked the answerers to rate based on their usefulness in the working life. There was also option for commenting the skill set and adding something that was missing.

The results show that both groups find the problem-solving skills the most important general skill. For the alumni the other two skills in top three were project management and team-work skills, whereas the people who might be hiring the graduates ranked programming and writing skills above them. From the field-specific skills understanding and implementing theories was the ranked as the most important. Other skills, such as data analysis or management of measuring process, were ranked in varying places depending on the duties of the person answering.

Based on the results we are going to critically evaluate our course contents and add components of problem solving and team working where possible.

What are the skills that we are teaching in our Master's program in Geoinformatics? How useful those skills are for the new graduates and which skills do they end up using in their working life? What are the skills that the companies that are hiring the new graduates are looking for?

As part of renewing our Master's program we asked our alumni which skills they have found useful in the working life. We also asked a group of our stakeholders to evaluate the same skills for the people they might be hiring. We had a set of predefined skills, both general and field-specific, that we asked the answerers to rate based on their usefulness in the working life. There was also option for commenting the skill set and adding something that was missing.

The results show that both groups find the problem-solving skills the most important general skill. For the alumni the other two skills in top three were project management and team-work skills, whereas the people who might be hiring the graduates ranked programming and writing skills above them. From the field-specific skills understanding and implementing theories was the ranked as the most important. Other skills, such as data analysis or management of measuring process, were ranked in varying places depending on the duties of the person answering.

Based on the results we are going to critically evaluate our course contents and add components of problem solving and team working where possible.

JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Outreach of climate change attribution in Hungary using seasonal indicators

DOI: 10.57757/IUGG23-4054 - LINK

Rita Pongracz[1], Peter Szabo[1], Judit Bartholy[1]
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The scientific community is well aware of the anthropogenic global warming and its consequences at regional level. However, the public is still not informed well enough, and may be confused especially due to the overwhelming, often contradictory social media environment. This is why we initiated a project with the aim to present and explain scientific results of regional climate change via a national platform (www.masfelfok.hu) established for climate awareness dissemination towards public, within this framework we also use a broad media platform and a large social media network as well. The message is formed as well-illustrated short studies focusing on various seasonally relevant climate indicators, mainly related to climatic extremes. The scientific background is based on calculations using reliable data: observation-based homogenized fine-resolution gridded data for Hungary (HUCLIM), outputs (i.e. CMIP6 data) from global climate model simulations with natural-only forcing as well as historical forcing (when anthropogenic concentration changes are also taken into account), regional climate model simulation outputs (i.e. EUROCORDEX data) for past decades (beginning from the last quarter of the 20th century) and future decades until the end of 21st century with strong mitigation, lighter mitigation, and non-mitigation scenarios. Studies are published in every 4-6 weeks, and online and traditional media connections are also used to outreach the public.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Educational and public outreach activities with a three-dimensional digital globe Dagik Earth

DOI: 10.57757/IUGG23-4750 - [LINK]()

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[1]Kyoto University, Department of Geophysics, Kyoto, Japan
[2]National Institute of Information and Communications Technology, Space Environment Laboratory, Tokyo, Japan
[3]Shizuoka University, STEAM Education Institute, Shizuoka, Japan
[4]NPO Dagik Earth Project, member, Kyoto, Japan

A three-dimensional digital globe system, Dagik Earth, has been developed by a group of geoscientists, software engineers, and educators for use in and out of school education and public outreach. The project aims to provide schools, science museums, and educators with the basic knowledge and recent progress in Earth and planetary sciences, and stimulate interest in them. The system is very simple and budget-friendly using a PC, a PC projector, and a spherical screen. The screen for this system is inexpensive, and any white sphere, such as a balance ball or balloon, can be used as the spherical screen. The three-dimensional presentation of the Earth and its data provides the audiences a view of looking down the Earth from space similar to large-scale three-dimensional globe systems, such as the Geo-cosmos of Mirai-kan, Japan, and Science On Sphere of the National Oceanic and Atmospheric Administration, USA. The software is provided free of charge for educational and scientific use. English and Chinese versions are also available although the majority of users are in Japan. A permanent exhibition of Dagik Earth is installed in 23 science museums, including one in Taiwan. As well as digital globe, the project is also developing analogue globes using global Earth and planetary science data. Students make their own handmade globes in classrooms and science events and take them home. In addition to introducing the software of Dagik Earth, we would like to introduce analogue craft materials in the presentation. International cooperation will also be discussed.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

Seismic risk communication over the past 20 years: An overview on time, methods and tools

DOI: 10.57757/IUGG23-1546 - [LINK]

Angela Saraò[1], *Gemma Musacchio*[2], *Susanna Falsaperla*[3], *Anna Scolobig*[4]
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[2]*Istituto Nazionale di Geofisica e Vulcanologia - INGV, Sezione di Milano, Milano, Italy*
[3]*Istituto Nazionale di Geofisica e Vulcanologia - INGV, Sezione di Catania - Osservatorio Etneo, Catania, Italy*
[4]*University of Geneva, Institute for Environmental Sciences, Geneva, Switzerland*

Risk communication has evolved significantly over the past two decades. In this study, we provide an overview of the timing, methods and tools we observed in a review study of earthquake risk communication in Europe.

Our study shows that communication occurs predominantly in the pre-event phase and that communication during the earthquake crisis is often limited to seismological information. Only one-fifth of the publications reviewed explicitly rely on theories of risk communication. There is an increasing convergence toward a two- or three-way communication model, i.e., the adoption of frameworks in which seismic risk experts promote proactive citizen participation; moreover, the goals of communication become more proactive than informative.

The goals of earthquake risk communication are to share information, raise awareness, change behaviors/beliefs, and increase preparedness. Students and citizens are the main target groups for communication activities. The involvement of schools is based on the idea of a 'domino effect," where students share and promote earthquake mitigation information and best practices within their families.

In an effort to reach an age-, culturally-, and educationally-diverse audience, traditional education/communication methods such as handouts and lesson plans are gradually giving way to exercises and hands-on activities, as well as more advanced communication tools such as infographics, video scribing, serious (video) games, and augmented reality applications. The results also show the growing role of social media as an information and dissemination channel.

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JH06 - Posters - Education & Outreach in Geosciences (IAHS, IASPEI, IAGA, IAG, IAVCEI, IACS, IAMAS, IAPSO)

KIDZ PAZ-NOWn - Increasing resilience to climate- and water-related natural hazards in Paznaun Valley via an inter- and transdisciplinary research-education-collaboration

DOI: 10.57757/IUGG23-4203 - LINK

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Lars Keller[2]*, Marke Thomas*[1]
[1]*University of Innsbruck, Dep. of Geography- Alpine Climate and Water Research ACWR, Innsbruck, Austria*
[2]*University of Innsbruck, Dep. of subject-specific Education- Education and Communication for Sustainable Development EDUCOMSD, Innsbruck, Austria*
[3]*Medical University of Innsbruck, Dep. of Psychiatrie II- Institut for Mental and Psychosomatic Illnesses, Innsbruck, Austria*

This poster presents the research framework of the transdisciplinary research project “KIDZ PAZ-NOWn”. The project aims to increase resilience to climate- and water-related natural hazards in Paznaun Valley (Tyrol, Austria), which looks back at a history of extreme weather events and natural hazards. Present-generation climate projections indicate that the region is expected to experience significant changes in temperature and precipitation with respective impacts on water-related natural hazards (e.g. the frequency and magnitude of floods). We apply the WRF-Hydro model, in conjunction with spatially and temporally refined climate scenarios from the CORDEX project, to simulate the impacts of climate change on the hydrosphere in Paznaun Valley. To account for glacier retreat in alpine environments, the new glacier mass balance model in WRF-Hydro will be expanded by a glacier flow routine. Model results will be discussed in a mutual learning alliance to promote a better understanding of the complex interaction between the climate and the water system in alpine regions as well as of the specific needs and vulnerabilities of mountain communities in the backlight of climate change. By strengthening the engagement between juveniles, hazard-relevant institutions from the local community and scientists from different disciplines, the project lays a solid foundation for lasting future resilience and the transformation of societies towards sustainability. As the valley represents a typical Alpine environment and is representative in terms of demographic and educational structure, the findings achieved in KIDZ PAZ-NOWn can be transferred to other alpine settings.

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JM03 - Posters - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Airborne remote sensing in the Arctic used to evaluate models and satellite observations

DOI: 10.57757/IUGG23-3848 - [LINK]

Mario Mech[1], *Susanne Crewell*[1], *Nils Risse*[1], *Imke Schirmacher*[1]
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The phenomenon of Arctic Amplification is most evident in the rise of the near-surface air temperature observed in the last decades being at least twice as strong as the global average. The mechanisms behind that are widely discussed. Many processes and their feedback mechanisms are still poorly understood, especially considering the role of clouds. To increase the understanding of such processes and to improve their representation in models, direct observations are needed, but are barely available. Within the research initiative "Arctic Amplification: Climate relevant atmospheric and surface processes and feedback mechanisms (AC)3", several airborne campaigns aimed to provide observations of clouds and precipitation by state-of-the-art remote sensing instruments.

Within this contribution, we will present measurements and datasets from the remote sensing suite operated onboard the Polar 5 research aircraft of the Alfred-Wegener Institute for Polar and Marine Research (AWI) during four airborne campaigns over the Arctic ocean and sea ice out of Svalbard. The measurements provide unique opportunities for the evaluation of satellite products and atmospheric models, e.g., cloud vertical structure, liquid water path, and sea ice emissivity. We assess models and reanalysis with two approaches: (i) model-to-observation via the forward simulator PAMTRA and (ii) the development of products from the observations from the synergy of cloud radar, lidar, and microwave radiometer measurements.

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JM03 - Posters - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Water vapor isotopic composition measurements at Dome C, East Antarctica, from 2018 to today: Isotopic signature of moisture intrusions

DOI: 10.57757/IUGG23-3859 - LINK

Ines Ollivier[1], Amaelle Landais[2], Thomas Lauwers[3], Christophe Leroy Dos Santos[3], Olivier Jossoud[3], Frederic Prie[3], Roxanne Jacob[3], Mathieu Casado[3], Elise Fourre[3], Hans Christian Steen-Larsen[4], Barbara Stenni[5], Cecile Agosta[3]
[1]University of Bergen and Bjerknes Center for Climate Research / CNRS, Geophysical Institute / LSCE, Bergen, Norway
[2]CNRS, Geophysical Institute / LSCE, Gif sur Yvette, France
[3]CNRS/CEA, Laboratoire des Sciences du Climat et de l'Environnement, Gif sur Yvette, France
[4]University of Bergen and Bjerknes Center for Climate Research, Geophysical Institute, Bergen, Norway
[5]Università Ca' Foscari Venezia, Dipartimento di Scienze Ambientali- Informatica e Statistica, Venice, Italy

Dome C is located on the high Antarctic plateau, at 3233m above sea level, and 1200km away from the coastline. At this location, the EPICA ice core was retrieved from the ice sheet and allowed the reconstruction of past climatic information 800,000 years back in time. Amongst several atmospheric parameters, the past local temperature was inferred from the stable water isotope record measured in the ice.

To interpret this record, it is necessary to understand how it was formed in such a dry and cold environment. This includes understanding the water cycle dynamics in Antarctica, from evaporation to precipitation and moisture pathways, as well as the processes affecting the record after deposition of the precipitation, such as snow-atmosphere exchanges.

During the austral summer 2018-2019, a Picarro laser spectrometer was installed on site to monitor continuously the isotopic composition of the atmosphere. It provided measurements for all austral summers since then and allowed the detection of two major atmospheric river events, including a rare event during the onset of the cold Antarctic winter. To go beyond the limitations of the Picarro instrument when measuring at very low humidity levels, as encountered during the wintertime at Dome C, a new laser spectrometer dedicated to low humidity measurements has been developed and installed it in parallel to the Picarro instrument during the summer season 2022-2023. Here we present the results of the atmospheric isotopic composition during four consecutive austral summers and the comparison of the two laser instruments during the most recent period.

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JM03 - Posters - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

New developments in laser spectroscopy for water vapor isotopic measurement along the Dumont-d'Urville – Dome C transect

DOI: 10.57757/IUGG23-3865 - LINK

Thomas Lauwers[1], Elise Fourré[1], Roxanne Jacob[1], Inès Ollivier[2], Olivier Jossoud[1], Frédéric Prié[1], Daniele Romanini[3], Mathieu Casado[1], Valérie Masson-Delmotte[1], Amaëlle Landais[1]
[1]Laboratoire des Sciences du Climat et de l'Environnement - IPSL, Unité mixte de recherche 8212- CEA-CNRS-UVSQ, Gif-Sur-Yvette, France
[2]University of Bergen and Bjerknes Center for Climate Research / CNRS, Geophysical Institute / LSCE, Bergen, Norway
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Water isotopes measurements in polar ice cores are key to reconstruct past climatic variations. However, the relationship between surface temperature and water isotopic composition is not straightforward because snow isotopic composition is influenced by many factors in addition to local temperature of condensation (evaporation origin, trajectory of moist air, post deposition effects). In order to refine this interpretation, parallel observation of water vapor and surface snow isotopic composition in polar regions is essential.

Measuring atmospheric water isotopic composition is however an important challenge, especially in dry places like the East Antarctic plateau, where water mixing ratio can be as low as 10 ppmv. Laser spectrometers based on the cavity ring-down spectroscopy (CRDS), commonly used for field measurement, fail to precisely measure water vapor isotopic composition for the lower range of water mixing ratios recorded in East Antarctica.

The optical feedback cavity enhanced absorption spectroscopy (OF-CEAS) technique offers an interesting alternative for low humidity detection. During the austral summer 2022 – 2023, two OF-CEAS spectrometers were respectively installed at Dumont-d'Urville, situated along the coast, and Dome C, situated on the plateau, at 3230 m above sea level. We present here results obtained with this OF-CEAS technique, which shows an improved limit of detection, while keeping a low humidity dependence.

This work is part of the AWACA ERC project, in which we intend to install several OF-CEAS instruments, in three remote sites situated along the Dumont-d'Urville – Dome C transect, in addition to the two permanent polar stations.

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JM03 - Posters - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Airborne remote sensing observations of Arctic low-level clouds and precipitation during cold air outbreaks

DOI: 10.57757/IUGG23-4355 - LINK

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[2]Universität Leipzig, Institut für Meteorologie, Leipzig, Germany

In cold air outbreaks (CAOs), cold and dry air flows from the central Arctic southward often leading to extreme weather at mid-latitudes. Roll convection in the boundary layer is triggered within the marginal sea ice zone. During the air-mass transformation, this roll convection leads to cloud formation within several 100 km away from the sea ice edge. Mixed-phase processes and extreme surface heat fluxes play an important role in the transformation. Understanding air-mass transformation is very important for weather and climate modelling. However, only few observations of cloud macro- and microphysical characteristics during CAOs along their trajectory exist yet.

Our study investigates cloud rolls over the open ocean and sea ice west of Spitsbergen using airborne remote sensing measurements obtained by the Microwave Radar/radiometerfor Arctic Clouds (MiRAC) and Airborne Mobile Aerosol Lidar for Arctic research (AMALi). We focus on two CAO events that took place during the HALO–(AC)3 campaign conducted in March/April 2021. The POLAR 5 aircraft flew several legs along the same track perpendicular to the cloud streets crossing the sea ice edge. This allows an investigation of the air masses with time and distance to sea ice edge. Hence, our analysis resolves the development of the roll convection. Dropsondes serve information of the thermodynamic state of the atmosphere, whereas remote sensing observations allow for a geometrical and microphysical analysis of clouds. In-situ measurements from the POLAR 6 aircraft, which flew collocated with P5 but inside the clouds, resolve aerosol number concentrations and droplet size distributions.

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The New Norwegian Infrastructure - Troll Observing Network - under Establishment in Dronning Maud Land, Antarctica

DOI: 10.57757/IUGG23-2802 - LINK

Christina A. Pedersen[1], Johannes Schweitzer[2], Birgit Njåstad[1], Wojciech Miloch[3], Wenche Aas[4], Stephen Hudson[1], Tore Hattermann[1], Elin Darelius[5], Sebastien Descamps[1], Rune Storvold[6], Stig Flaatt[1], Stein Tronstad[1]
[1]Norwegian Polar Institute, Research Department, Tromso, Norway
[2]NORSAR, Applied Seismology, Lillestrøm, Norway
[3]University of Oslo, Physics Institute, Oslo, Norway
[4]Norwegian Institute for Air Research, Department for Atmosphere and Climate, Lillestrøm, Norway
[5]University of Bergen, Geophysical institute, Bergen, Norway
[6]NORCE, Drones and Autonomous Systems group, Tromso, Norway

Antarctica and the Southern Ocean are important parts of the Earth system. The physical and biological properties here to a large degree control and shape other parts of the Earth through atmospheric, cryospheric and oceanic connections.

The Troll Observing Network – TONe - is a new comprehensive infrastructure centered around the Norwegian Troll Research Station in Dronning Maud Land. It will be an important contribution to global research efforts in this part of Antarctica, closing data gaps in Antarctic environmental observations and providing key data required to respond to the fundamental societal challenges and uncertainties facing the world today.

The Norwegian and international partner consortium in TONe is in the process to develop the state-of-the-art, multi-platform, multi-disciplinary observatory network for environmental observations, and a remotely piloted aerial system (RPAS) services to collect data for studying and monitoring the atmosphere, terrestrial and marine environment. The observatory network consists of 8 observatories: an integrated cloud observatory, an atmosphere composition observatory, an infrasound array, an ionospheric observatory, a seismic array, an ice-shelf observatory, a multidisciplinary open ocean moored observatory and a sea-bird observatory.

The key aspect of TONe is to ensure wide and free access to the data from the observatories and the RPAS services to the entire national and international research community.

TONe as a whole will be implemented and fully operational from 2027, while single parts of the infrastructure will be available before that.

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JM03 - Posters - Polar Regions Instrumentation (IAMAS, IACS, IASPEI)

Turbulent fluxes measurements in coastal Antarctica in the framework of the AWACA Project.

DOI: 10.57757/IUGG23-2938 - LINK

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[2]*CNRS, Laboratoire Atmosphères- Observations Spatiales LATMOS - IPSL, Guyancourt, France*
[3]*École Polytechnique Fédérale de Lausanne EPFL,*
Environmental Remote Sensing Laboratory LTE, Lausanne, Switzerland

The AWACA (Atmospheric WAter Cycle over Antarctica) project aims to deploy 4 OPUs (Observation Platform Units) along a 1100km transect from coastal Terre Adélie to the interior of the high-elevated antarctic plateau. They will perform condensed water measurements throughout the atmospheric column. Surface meteorological conditions near the OPUs will be monitored with a 7m tower mast, the first prototype of which was deployed during the last summer campaign 2022-23.

This setup includes a sonic anemometer, which gives access to turbulent momentum and heat fluxes near the snow surface. The collected measurements will enable the investigation of those fluxes which remain scarcely studied especially in the winter season and in the interior of the continent due to harsh meteorological conditions.

The context of the AWACA Project and the meteorological tower's design will be illustrated, and the first results from the summer campaign depicted and analyzed.

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JP01 - Posters - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Temporal stability of strain tides in southern California, 1971-2021

DOI: 10.57757/IUGG23-4348 - LINK

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Tidal forces, by providing a well-known, though narrowband, input to the Earth and ocean, are very useful for detecting temporal changes in the response of these systems. Strain tides provide the most sensitive tidal measurement of local changes in the elastic behavior of the solid Earth for two reasons. First, unlike tilt and gravity, strain tides have no component from the direct attraction. Second, measuring the derivative of displacement makes strain measurements more sensitive to nearby changes than displacement measurements would be; changes in elastic constants are more likely at shallow depths. We report on temporal variations in strain tides observed on long-base laser strainmeters at five locations in Southern California. Since the overall data span is almost fifty years at some locations, and mostly more than a decade, these data provide an unmatched dataset for examining the stability of strain tides. The calibrations depend mostly on instrument length and the wavelength of light, both invariant with time, along with two electronic systems of high stability. A first look at a portion of the data from a few sites shows high stability for the semidiurnal tides; the diurnal tides show seasonal patterns driven by unavoidable thermal effects on the instrument systems, which produce a spurious S1 tide. Results from a fuller analysis will be compared with postseismic inelastic effects from large earthquakes in 1992, 1999, and 2010, along with water-well tides at one site, which have shown temporal variations.

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JP01 - Posters - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Arctic ocean tidal constituents atlas

DOI: 10.57757/IUGG23-3651 - LINK

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[6]The University Centre in Svalbard, Research Centre in Svalbard, Longyearbyen, Norway

Ocean tides are a vital component of global ocean circulation, with their role in the Arctic Ocean being crucial for ocean and sea ice dynamics. Recently, significant advances have been made in global ocean tide models, however, difficulties remain in the coastal regions as well as in the higher latitudes. The latter is related to the poorly resolved bottom topography, the influence of sea ice and limited regular satellite altimetry measurements. Although modelling efforts are attempting to improve our ocean tide estimates in the Arctic Ocean, the tidal in-situ network is an additional limiting factor in this region. In-situ measurements from tide gauges or ocean bottom pressure sensors are crucial sources of information that can be used to understand the spatial variability of tides as well as validate the advances made in modelled estimates. However, globally in-situ tidal constituent databases contain a limited number of observations with, for example, TICON-3 containing 111 above 60°N and 21 above 70°N with the distribution of these measurements mainly being around North America. This abstract presents the results of a concerted effort to produce a harmonised dataset of tidal constituents in the Arctic region. This dataset combines in-situ measurements from tide gauges, ocean bottom pressure sensors and GNSS reflectometry, which results in approximately 691 measurements above 60°N and 313 above 70°N with a much greater spatial distribution across the full Arctic ocean. The resultant dataset is quality assessed and compared to recent tide models to determine the reliability of the different data sources used.

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pressure sensors and GNSS reflectometry, which results in approximately 691 measurements above 60°N and 313 above 70°N with a much greater spatial distribution across the full Arctic ocean. The resultant dataset is quality assessed and compared to recent tide models to determine the reliability of the different data sources used.

JP01 - Posters - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Radiational tides and forecasting storm surges

DOI: 10.57757/IUGG23-2479 - LINK

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[1]National Oceanography Centre, Liverpool, Liverpool, United Kingdom
[2]UK Met Office, Modelling, Exeter, United Kingdom
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In the UK, Coastal Flood Forecasting procedures rely on forecasts of still water level generated by combining predicted tide and storm surge components. The tide component of this system is often termed the 'astronomic tide'. However, the predicted tide is derived from a harmonic analysis of the full water level time-series (tide plus surge) observed at tide gauges – typically from the last 19 years. Therefore, the tidal predictions will include radiational tides particularly those that occur with tidal frequencies such as S_2 and Sa.

We have previously shown that the current forecasting system double-counts several cm of tides from these sources, since the radiational tides are also generated by the surge model. Now we investigate further, to see whether removing a modelled surge prior to tidal analysis and prediction can improve total water level forecasting.

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JP01 - Posters - Tides (IAPSO, IAHS, IAGA, IASPEI, IAG)

Comparisons of a revised tidal Response Method with modern Harmonic Analysis

DOI: 10.57757/IUGG23-3989 - LINK

Thomas Monahan[1], *Tianning Tang*[1], *Thomas A. A. Adock*[1]
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While tidal Harmonic Analysis (HA) has seen considerable development in the past 50 years, the Response Method, as described in the seminal paper of Munk and Cartwright, has remained relatively stagnant. The principal advantage of the response method is the inclusion of Kepler-Newtonian mechanics which avoids the need to split species into discrete spectral clusters. Additionally, the physical basis of the response framework allows for the systematic study of non-linear processes which are not well understood and play a significant role in shallow-water regions. Despite these advantages, HA remained and remains the tool of choice for tidal analysis due to the non-trivial burden of selecting realistic input functions. As such, a data-driven response analysis procedure is proposed for the automatic selection of input functions. We present comparisons between the proposed method and the state-of-the-art harmonic analysis. Additionally, a framework for the study of non-linear processes using response analysis is presented, and a Python implementation is provided.

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JP04 - Posters - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Changes in the physical properties of Antarctic shelf water due to global warming

DOI: 10.57757/IUGG23-4815 - LINK

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[2]Korea Polar Research Institute, Division of Ocean Sciences, Incheon, Korea Republic of

The Antarctic continental shelf plays a critical role in global climate system as a buffer zone of the heat and material exchange between Southern Ocean and Antarctica. To investigate the response of physical properties for Antarctic shelf waters in response to increasing atmospheric greenhouse gases, we present a comparison of a fully coupled global climate model, Community Earth System Model version 1.2.2, results between present-day climate run (PC, atmospheric CO_2 is fixed to 367 ppm) and future climate run (FC, atmospheric CO_2 is double to 734 ppm). The latter experiment was branched from 71 year of the control run for 140 years and was integrated for another 100 years. The last 20 years of both simulations were analyzed. The resulting physical properties of Antarctic shelf waters reproduced by PC are generally consistent with what has been known by previous studies except for the Prydz Bay where the considerably warm (T>0.5C) water was simulated and the Cape Darnley where the outflows of dense shelf water were vanished. The FC results demonstrate significant warming (T>0.5°C) on the shelves in Amundsen Sea, Bellingshausen Sea, and eastern Ross Sea, and off the Adelie and Budd coasts, and freshening all over the Antarctic shelves, suppressing the Antarctic bottom water formation. The results suggest weakening of deep and abyssal circulation by suppressed bottom water formation due to increased atmospheric CO_2 concentration along with the potential for more rapid melting of Antarctic ice sheets.

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JP04 - Posters - Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Coupled ocean-ice sheet modelling of the Amundsen Sea Embayment, West Antarctica

DOI: 10.57757/IUGG23-2664 - LINK

Antony Payne[1], Ruth Mugford[1], Felipe Gomez Valdivia[2], Matt Trevers[1], Paul Holland[2], Kaitlin Naughten[2], Robin Smith[3]
[1]University of Bristol, School of Geographical Sciences, Bristol, United Kingdom
[2]British Antarctic Survey, Polar Oceans, Cambridge, United Kingdom
[3]University of Reading, National Centre for Atmospheric Science, Reading, United Kingdom

Here we present initial results from a coupled configuration of the BISICLES ice sheet and NEMO ocean models for the Amundsen Sea Embayment. We use NEMO 4.2 with ice shelf cavity circulation enabled on a 0.25 degree horizontal grid with 75 vertical levels. Our initial focus is on producing a credible simulation of recent changes in the oceanography of the area before comparing the patterns of ice shelf melt predicted by NEMO with those required by BISICLES to generate patterns of ice thinning and grounding line retreat similar to observations. Forcing for these experiments comes from the UKESM CMIP6 simulations, currently for the historical period but with the intention of producing projections to 2100 of ice loss from the area.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Simulation and Spectral analysis of the 2016 Fukushima earthquake tsunami in Sendai Bay, Japan

DOI: 10.57757/IUGG23-0648 - LINK

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[2]*Tohoku University, International Research Institute of Disaster Science, Sendai City, Japan*

The November 2016 Mw 6.9 Fukushima earthquake tsunami was a fresh call for potential large and long duration of tsunamis in Sendai Bay associated with the normal-faulting earthquake. The maximum tsunami height of 1.4 m and duration for more than 34 h was observed at Sendai port. Here, we conducted spectral analyses to sea level records at five tide gauges and tsunami simulation to shed light on the source characteristics and various coastal and shelf features such as reflections, trapped edge waves, as well as resonance of the wave on the shelves. We reproduced the tsunami source spectrum by calculating the ratio of tsunami and background spectra. Based on the source spectrum, the short-axis source dimension was identified as 30 km, which is consistent with the source models proposed by Gusman et al., 2017 and Adiano et al., 2018. In addition, we identified the main oscillation periods of the 2016 Fukushima earthquake tsunami at 9-38 min. Based on those periods, we performed spectral analyses of simulated tsunami wavefield in the region of interest, including Sendai Bay, Oshika Peninsula, and southern part of Sanriku coast. Tsunami resonance is a coastal process that occurs when the tsunami periods match the natural periods of Bays or continental shelves. Our analyses showed significant energy amplification inside the Sendai Bay at certain periods owing to resonant oscillation. Our findings have implication for tsunami warnings and disaster risk reduction for future tsunamis.

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Numerical simulation and experiment on Tsunami of high viscosity and density fluid containing sediment

DOI: 10.57757/IUGG23-3463 - LINK

Yota Enomoto[1], *Taro Arikawa*[1]
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It has been observed that huge tsunamis such as the Great East Japan Earthquake cause black, muddy water to overflow and run upstream. This is presumably due to the large amount of sediment carried by the tsunami. Although many studies have been conducted on such sediment-containing flows, the effects of sediment on tsunamis have not been dealt with much. A tsunami containing sediment may become a non-Newtonian fluid due to its increased density and viscosity. In fact, Nakamura et al. confirmed that a tsunami containing a certain amount of silica sand becomes a Bingham fluid. In this study, numerical simulations of a tsunami inundation flow containing sediment are conducted to investigate the effect of the viscosity change on the tsunami wave force. In the numerical simulations, the Bingham model was applied to the CADMAS-surf3D/2f fluid analysis model to reproduce the spatiotemporal changes in viscosity. Coupled calculations with a sediment transport model were also used to calculate sediment roll-up and reproduce changes in density. The validity of the simulations was verified by comparison with experiments. The model was then used to perform numerical simulations under local conditions to verify the change in tsunami behavior due to sediment roll-up. The results showed that the viscous effect increased the tsunami overtopping height, and coupled with the density effect, the quasi-steady sustained wave pressure was larger than that of pure water. Furthermore, the increase in tsunami density due to sediment roll-up was found to be larger for finer particles.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Experimental study on tsunami generated by three-dimensional landslides

DOI: 10.57757/IUGG23-1379 - [LINK]

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[1]*Tokyo Electric Power Services Co. Ltd.-, Civil Engineering Div., Tokyo, Japan*
[2]*Central Research Institute of Electric Power Industry, Nuclear Risk Research Center, Chiba, Japan*
[3]*Chubu Electric Power Co.- Inc.-, Nuclear Power Division, Aichi, Japan*

Since tsunamis generated by submarine and subaerial landslides occur less frequently than tsunamis generated by fault movement, the actual behavior of landslide tsunamis is not well understood. Experimental and analytical studies have been conducted on submarine and subaerial landslide tsunamis, but there are fewer research examples than tsunamis generated by fault movement. In addition, experiments using two-dimensional flume have been mainly conducted, and there are few examples of examinations of submarine and subaerial landslide tsunamis under the same conditions. In this study, granular and solid slide models were used as models of landslide bodies, and hydraulic model experiments of submarine and subaerial landslide tsunamis were conducted by three-dimensional landslides. The 12.0m long, 12.0m wide, and 1.5m high experimental water tank was constructed, and landslide models were installed on the top of the slope. As the shape of the landslide model, three kinds of solid slide models were used as non-deformable landslide bodies, and granular bodies were used as deformable landslide bodies. We investigated the tsunami water level generated by the difference between granular material and solid slide model, and the difference between submarine and subaerial landslides, and its propagation process. The experimental data obtained in this study are useful for verification of the landslide tsunami numerical simulation model.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Examining the reliability of historical teletsunamis reaching Japan using literature review

DOI: 10.57757/IUGG23-0802 - LINK

Yutaka Hayashi[1]
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The NGDC/WDS Global Historical Tsunami Database (GHTD; NCEI) includes thirteen tsunami cases recorded in Japan, accompanied by foreign earthquakes until 1900. Following a literature review, false tsunami information based on errors in Japanese documents and historical interpretations was found in GHTD; five out of thirteen cases were false teletsunamis. Therefore, the reliability of historical tsunami data cannot be ensured without collaboration among researchers with different nationalities.

List of false teletsunamis to Japan found through literature review:
(1) The earthquake in Chile on 6 September 1420: Both earthquake and tsunami occurrence in Chile or Peru on 6 September 1420, and teletsunami occurrence in Ibaraki Prefecture on that date are groundless [1].
(2) The earthquake in Peru on 10 July 1586: This earthquake and an oral tradition in Japan are unrelated [2].
(3) The Philippines earthquake on 14 September 1627: This earthquake and the historical material on tsunamis in Japan are unrelated, and the date of the earthquake can be identified only by the month [1].
(4) The earthquake in Peru in 1651: No evidence of a tsunami caused by the 1651 earthquake in Peru. No reliable document on the event found in Japan [1].
(5) Earthquake along the Kuril Islands on 29 September 1780: The only economic impact on Japan was from the tsunami [3].

Reference:
[1] Hayashi, Japan Geoscience Union Meeting 2023, S-SS13, submitted.
[2] Hayashi et al., Quarterly Journal of Seismology, 81:9, 2018. (in Japanese with English abstract)
[3] Hayashi, Historical Earthquakes, 38, in print. (in Japanese with English abstract)

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Experiments on saturated suspended sediment concentration in tsunami flow

DOI: 10.57757/IUGG23-0632 - LINK

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[1]*Central Research Institute of Electric Power Industry, Nuclear Risk Research Center, Chiba, Japan*
[2]*Tokyo Electric Power Services Co.- Ltd., Civil Engineering Div., Tokyo, Japan*
[3]*Chubu Electric Power Co.-Inc., Nuclear Power Division, Aichi, Japan*

The saturated suspended sediment concentration in tsunami flow was experimentally investigated in this study. The large-scale tsunami physical simulator of Central Research Institute of Electric Power Industry was used for the experiments. The flume was composed of 5m long flat and non-movable bed at the upstream side and 20m long initially flat movable bed with a sand layer at the downstream side. Fast inundation flows with the velocities of approximately 3 m/s and inundation depths of approximately 0.4m passed over the bed and entrained suspended sediment from the sand layer. As going to the downstream side, the suspended sediment concentrations increased and appeared to approach equilibrium/saturation states. The saturated suspended sediment concentration which were measured were compared with the classical theory of Bagnold (1966), and good agreement among them was confirmed.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Numerical simulations of landslide-generated tsunamis using dispersive two-layer model

DOI: 10.57757/IUGG23-0661 - LINK

Tatsuto Kimura[1], Naoto Kihara[2], Hayato Mori[3], Naoki Fujii[1]
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Fujii et al. conducted three-dimensional experiments to investigate the generation and propagation of tsunamis caused by landslides. They used granular materials or solid slide models as the landslides and switched between submarine and subaerial landslides by changing the initial water level. In this study, the two-layer model was validated using the results of their granular subaerial landslide experiments. Although calculated water levels using the original two-layer model based on the nonlinear shallow water equations significantly differed from the measurements, the addition of the dispersion term to the upper-layer equation resulted good agreement. The dispersive two-layer flow model can predict the water level of tsunamis caused by subaerial landslides comparable to the three-dimensional model, and is advantageous in terms of computational cost.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Three-dimensional numerical simulation of landslide-generated tsunamis

DOI: 10.57757/IUGG23-0663 - LINK

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In this study, three-dimensional numerical simulations using OpenFOAM for tsunamis generated by submarine and subaerial landslides, were verified by comparison with the results of hydraulic model experiments conducted by Fujii et al. MultiphaseInterFoam was used for the solver and the landslide was modeled as a dilatant fluid. It was clarified that the grid size must be appropriately set to reproduce the short wave propagating to the shallow water area in the case of submarine landslide. The calculated thickness of the landslide at the start of the movement was consistent with that of the experiment, but the spread in the direction orthogonal to the slope was narrower than in the experiment. By examining the validity of the analysis for three-dimensional experiments rather than two-dimensional experiments, the issue of reproducibility of the flow shape and depositional area of the landslide body was clarified.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Damage Response of Coral Reefs during the 2004 Indian Ocean Tsunami

DOI: 10.57757/IUGG23-1299 - LINK

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The impact of tsunamis on buildings, infrastructures and human losses has been globally studied. However, the relationship tsunami waves-marine ecosystems remains unclear. For example, during the 2004 Indian Ocean Tsunami (IOT), damage to living corals and reefs were surveyed all over the archipelago. Given that coral reef system is essential for fisheries, tourism and represent a natural coastal protection against large waves events, it is urgent to better understand how the IOT damaged such an ecosystem. Using TUNAMI-N2 model, we propose to reproduce the maximum amplitude and flow velocity of the IOT along the Maldivian shores with 10-m resolution. From statistical analysis, we developed tsunami fragility curves, with their 95 % confidence interval, for damaged coral reefs based on the maximum tsunami amplitude and the maximum flow velocity of the IOT. The flow velocity is found to be the best descriptor of tsunami damage. Based on the results, when the tsunami amplitude and flow velocity attain 4 meters and 4 m/s respectively, the probability that reefs endure damage is about 80 %. This founding may have implications for the development of long-term reef monitoring and planning to strengthen the resilience of reef resources after large wave events in the Maldives.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Real-time mapping of population exposure to tsunami hazard from human mobility data

DOI: 10.57757/IUGG23-2532 - LINK

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The population at risk of tsunami varies according to the season, day of the week, time, etc. Thus, even the same tsunami hazard may pose different levels of risk for an area with high mobility of residents and tourists. In the context of the efforts to develop the Tsunami Digital Twin (TDT) (Koshimura et al., 2023) for Japan, we investigated the application of human mobility data for real-time population exposure estimation. We selected two target areas prone to the anticipated Nankai Trough Earthquake, Katsurahama beach and Tanezaki district in Kochi Prefecture. The areas near Katsurahama correspond to a low residency but highly touristic zone, while Tanezaki is a highly residential area with low tourist activity. The size of both sites is similar for comparison, and the expected tsunami runup is in the same order of magnitude. The tsunami inundation is based on the scenarios proposed by the Cabinet Office of Japan. As the human mobility data, we used "Mobile Spatial Statistics" (DOCOMO InsightMarketing) containing estimated hourly population counts based on mobile phone networks. We found significant variations in the expected number of people at risk of tsunami during a year. Population dynamics affect the necessary levels of response and assistance. Furthermore, we show a prototype of our newly developed Population Exposure Mapping System (PoEMS) applied to real-time tsunami risk assessment.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Proposal of Balloon-Type Signs for Tsunami Evacuation Buildings

DOI: 10.57757/IUGG23-1503 - LINK

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[3]*International Research Institute of Disaster Science- Tohoku University, Risk Evaluation and Disaster Mitigation Research Division, Sendai, Japan*

Since the 2011 Tohoku earthquake and tsunami, each municipality in coastal areas has constructed and designated a lot of Tsunami Evacuation Buildings (TEB), the sites for secure physical safety under tsunami threat. The total number of them in Japan is more than 15,000 at present. The municipalities have concurrently developed tsunami hazard maps and evacuation signs to inform people of their locations. However, previous surveys point out the low awareness of their locations among people, especially visitors. Therefore, those who should quickly evacuate from the tsunami cannot decide their destination smoothly. In particular, the popular touristic sites along the coastal area require a solution to guide visitors who are not familiar with the TEB. It is necessary to highlight their locations intuitively to complete evacuation as soon as possible. For this reason, this study examines the use of balloon-type evacuation signs as visual information to lead people within a wide area to the sites before the tsunami arrives. This study consists of experiments in real space and virtual space. In real space, we set up balloon-type evacuation signs with different design and delimit the area for which the balloons can be seen. On the other hand, in the virtual space, we measure the evacuation time and the people trajectory with and without the presence of these signs. Through these experiments, we could evaluate the social implementation value of tsunami evacuation guidance with balloon-type evacuation signs.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Analysis and characterization of the 2020 Kuril Islands event by inversion of tsunami waves

DOI: 10.57757/IUGG23-4720 - LINK

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The Kuril Islands trench has produced major tsunami events that have propagated towards different coastal areas in the Pacific Ocean basin. A tsunami wave inversion is performed to characterize the initial sea surface distribution triggered by the 2020 Kuril Islands earthquake (Mw 7.5). The tsunami generated by the earthquake caused a small appreciable tsunami wave at stations 21415, 21416 and 21419 of the DART network. To calculate the elementary waveforms (Green's functions) associated with each subfault and station, tsunami simulations are performed using the EasyWave code (Babeyko, 2012). This formulation solves the shallow water linear equations on a grid in spherical coordinates. A GEBCO bathymetry with a resolution of 30 arc-sec (~900 m) is used and a 90-minute propagation period of the tsunami is simulated. Once the Green's functions have been calculated, we proceed to solve the linear system using the algorithm of least squares following the method developed by Tsushima et al. (2009). Tsunami waves on DART buoys are adequately reproduced. The results are compared with the waveforms based on the finite fault solution obtained by the United States Geological Survey.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Tsunami forecasting variability as resulting from slip models obtained by geophysical data inversion and by a Phase Variation Method

DOI: 10.57757/IUGG23-4640 - LINK

Fabrizio Romano[1], Patricio Catalan[2], Stefano Lorito[1], Cipriano Escalante Sanchez[3], Simone Atzori[1], Thorne Lay[4], Roberto Tonini[1], Manuela Volpe[1], Alessio Piatanesi[1], Jorge Macias Sanchez[5], Manuel Castro Diaz[5]

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[2]Universidad Técnica Federico Santa María, Department of Civil Engineering, Valparaiso, Chile

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The accurate estimate of the tsunami forecast is crucial in Tsunami Early Warning Systems (TEWS) framework. However, the inherent uncertainties associated with the tsunami source estimation in real-time make tsunami forecasting challenging.

In this study, we consider the South American subduction zone, one of the most seismically active regions in the world, where in the last 15 years occurred, three M8+ tsunamigenic earthquakes; in particular, we focus on the 2014 Mw 8.1 Iquique event.

Here, we compare the tsunami forecasting for the Chilean coast as resulting *i)* from the coseismic slip model obtained by geophysical data inversion and *ii)* from an expeditious method for the tsunami source estimation, based on an extension of the well-known spectral approach.

In the former method, we estimate the slip distribution of the 2014 Iquique earthquake by jointly inverting tsunami waveforms and GPS data; on the other hand, a set of stochastic slip models in the latter is generated through a Phase Variation Method (PVM), where realizations are obtained from both the wavenumber and phase spectra of the source.

We also evaluate how the different physics complexity included in the tsunami modelling (e.g. by including dispersion or not) can be mapped into the tsunami forecasting uncertainty. Finally, as an independent check, we compare the predicted deformation field from the slip models (inverted or by PVM) with the RADARSAT-2 InSAR data.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Simulation of drifting aquaculture facilities in Yamada Bay during the 2022 Tonga volcano eruption and tsunami

DOI: 10.57757/IUGG23-1297 - LINK

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[1]*National Defense Academy, Department of Civil and Environmental Engineering, Yokosuka, Japan*
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A tsunami triggered by the eruption of an undersea volcano off the coast of Tonga in January 2022 caused damage to aquaculture facilities along the Japanese coast. Since damage to aquaculture facilities by non-seismic tsunamis, which have a shorter period than seismic tsunamis, is unprecedented, it is important to elucidate the damage mechanism. In this study, drifting simulations of aquaculture facilities in Yamada Bay were conducted to clarify the damage process of aquaculture facilities caused by this event.

The tsunami propagation was based on the nonlinear shallow water equations, and the water level waveforms observed by GPS wave gauges were input from the boundary. The drift of the aquaculture facility was represented by a rigid body model, and the hydrodynamic forces caused by the tsunami were applied to the model. The location of the aquaculture facilities was obtained from Google Earth satellite images of Yamada Bay, and the weight and size of the aquaculture products were given as parameters based on information obtained from field surveys conducted by the authors.

Numerical results indicated that the water level tended to rise at the back of the bay and the flow velocity tended to increase at the mouth of the bay and on topographic features such as capes. There was a positive correlation between the flow velocity and the drift distance of aquaculture facilities, which was especially significant in the affected areas. Even small tsunamis may have a significant impact on the location of aquaculture facilities in the bay.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Proposal of disaster risk reduction learning program through interviews with disaster survivors at junior high school in the affected area

DOI: 10.57757/IUGG23-1341 - LINK

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An appropriate tsunami evacuation behavior is effective in reducing human casualties from tsunamis. One of the ways to promote their behaviors is learning about disaster risk reduction especially preparedness before a disaster occurs. Thus, many elementary schools and junior high schools in Japan have been conducting disaster education programs to learn about disaster risks in their community. In this study, we incorporate interview survey into disaster education program and study the learning effects of interviewing residents who experienced disaster about their experiences at the time of a disaster to be shared for the future. By concentrating on the residents' experiences during the disaster, it is expected that the interviewer will be able to relive the residents' behavior during the disaster. Furthermore, the interviewed residents' experiences of disasters are expected to provide lessons on what actions to take and how to prepare for disasters, and to improve individual disaster preparedness. In addition to learning disaster risk reduction, it is expected that students will acquire abilities necessary for living, such as the ability to understand people's stories and the ability to communicate with others, through interviews. By conducting a questionnaire survey before and after the disaster education and statistically analyzing, we will clarify the effects of the disaster education including interviews on the ability to cope with disasters and on other abilities necessary for students' life.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Products and services available from U.S. NOAA NCEI archive of tsunami water level data

DOI: 10.57757/IUGG23-0446 - LINK

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The U.S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) archives analog and high-resolution digital coastal water level data and ocean-bottom pressure data, digitizes select analog data, and performs quality-control and tidal analysis of these data. The analog tide gauge records (marigrams) cover selected tsunami events between 1854 and 1994 observed at stations across the globe. The digital tide gauge data, primarily U.S. stations, have been collected at 1-minute sampling since 2008. The ocean-bottom pressure data have been collected since 1983. These time-series data are complementary to the maximum wave heights recorded in the NCEI/World Data Service Global Historical Tsunami Database. All water level data and products are converted to standardized file formats to reduce barriers to re-use. We provide quality-controlled water level data, computed astronomical tides, details on the harmonic tidal analysis results, and spectra to assess the quality of the de-tiding. Researchers use the quality-controlled data to validate tsunami propagation and storm surge models. In the event of a tsunami, we augment our holdings by collecting and processing data from the National Hydrographic Services in the affected regions and from the United Nations Education, Scientific and Cultural Organization Intergovernmental Oceanographic Commission (UNESCO IOC) Sea Level Stations Monitoring Facility. These data products are then made available via Tsunami Event Pages. This presentation will provide an overview of NCEI's water level data availability and processes.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Effect of water density on wave pressure due to bore-like tsunamis

DOI: 10.57757/IUGG23-4923 - LINK

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The tsunami caused by the Great East Japan Earthquake of 2011 was called a black tsunami, and it was mixed with sediments, which was observed in many areas. Most of the previous studies on tsunami loading have been based on experimental and numerical calculations using fresh water, and the effects of sediment contamination have rarely been investigated. This study conducted bore-like tsunami pressure experiments with various densities to clarify the mechanism of impulsive wave pressure due to density changes. For validation, numerical calculations were performed on the same model used in the experiment, followed by calculations on local conditions. The average impulsive wave pressures of silt-mixed water, sand-mixed water, and freshwater were compared in terms of the Froude number. Under these conditions, the impulsive wave pressure due to sediment-mixed water was found to be in some cases greater than that with fresh water. The relationship between the water surface angle and wave pressure at impact was also investigated. The results revealed large variations. In silt-mixed water, the impulsive wave pressure tended to increase as the water surface angle at impact increased. Numerical results show that a 4% increase in density results in a 15% increase in maximum wave pressure. Additionally, an increase in the water surface angle was also observed. Numerical calculations performed under local conditions confirmed the increase in wave pressure due to sediment-mixed water. Wave pressure against the wall surface of the sediment mixture tends to increase but can be evaluated by the freshwater wave pressure rating index.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Capability of inversion of dense offshore tsunami measurements to constrain spatio-temporal evolution of tsunami source process

DOI: 10.57757/IUGG23-3548 - LINK

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This study discusses the spatio-temporal evolution of tsunami source process in real-time tsunami forecasting. Previously, we developed a tsunami forecasting method based on the real-time source inversion using offshore tsunami waveforms. In the method, the source process is assumed to finish instantaneously at the time of an earthquake, whereas the source process of actual huge earthquakes is spatio-temporally complex. The offshore tsunami data from the dense seafloor observation networks around Japan may enhance to constrain the spatio-temporal evolution. To design the improved forecasting method that is versatile for tsunamigenic earthquakes with various spatio-temporal source processes, this study conducted synthetic tests of tsunami forecasting, focusing on how well the offshore tsunami waveforms can constrain the time evolution of the source process. Synthetic data for ~170 offshore tsunami-meters along the Japan trench were produced by numerical tsunami simulation assuming the fault model of the 2011 Mw 9.0 Tohoku earthquake. Synthetic tests were conducted under various conditions by independently varying the source duration assumed in production of the synthetic data and the that used in the inversion. The results showed two suggestions for accurate forecasting of coastal tsunami heights. The first suggestion is that it is important to avoid situations that source duration used in the inversion is much shorter than that of the targeted earthquake. The second suggestion is that using a very long source duration for the inversion is effective for both the long- and short-source-duration earthquakes.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Hydraulic Experiments on Sediment Trapping Capacity by Types of Coastal Vegetation in Chiba Pref.

DOI: 10.57757/IUGG23-2205 - LINK

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Coastal forests have disaster-prevention effects such as reducing the force of tsunami waves and trapping drifting debris. On the other hand, sediment runoff from the coastal forest floor can cause the forest to driftwood, increasing the damage. The forest floor environment is composed of a wide variety of coastal vegetation. Although these vegetations have the effect of preventing blowing sand, their sediment trapping effect against tsunamis is unknown. The objective of this study is to elucidate the sediment trapping effect of coastal vegetation through hydraulic experiments. The samples were collected from coastal vegetation from the front edge of coastal forests in Chiba Prefecture, Japan.

The vegetation samples were placed in a sand box in a two-dimensional water channel, and waves were generated to measure the amount of sediment transported from the sand box. The generated waves were a bore wave simulating the tip of a tsunami and a steady flow simulating the passage of a tsunami. The water level and velocity in the channel were measured in a fixed-bed experiment. The flow conditions were checked during the experiment by video recording from above and from the side of the sand-bed box.

The results showed that sediment transport decreased with increasing vegetation coverage. In the case of multiple bore wave events, it was suggested that the type of vegetation and the amount of rhizomes may also affect the amount of sediment transport.

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JP05 - Posters - Tsunamis (IAPSO, IASPEI, IAVCEI, IAMAS, IAG)

Children’s awareness and the effects of disaster prevention education: Impact of the great east Japan earthquake tsunami

DOI: 10.57757/IUGG23-1423 - LINK

Mari Yasuda[1], *Ryo Saito*[1], *Toshiaki Muramoto*[1]
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This study investigated trends in disaster preparedness awareness among elementary school children in Miyagi and Fukushima prefectures. Questionnaire surveys conducted before, immediately after, and one month after the delivery classes revealed regional differences in children's disaster awareness.Compared to coastal areas, inland areas had relatively lower disaster awareness. Children in the coastal area of Fukushima were highly motivated to learn about disaster prevention, and their disaster risk assessment increased even after the on-site class, and remained high one month later, indicating the influence of the earthquake off the coast of Fukushima Prefecture, which occurred frequently from the Great East Japan Earthquake to the present and continued to occur even after the delivery classes. The Miyagi coastal area has a high awareness of evacuation behavior in the event of a disaster, suggesting that the importance of evacuation behavior may be shared within the family due to the many past tsunami disasters. The Fukushima inland area showed a high fear of natural hazards and a tendency to lack confidence in their actions in the event of a disaster, while the Miyagi inland area showed low fear of disasters, assessed low disaster frequency, and showed low interest in family commitments. Finally, this study suggests the factors that influence the effectiveness and sustainability of disaster prevention education for children including the geographical characteristics of the region, past disaster experiences, and the number of local disaster training programs.

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Reproduction of tsunami attenuation effects by coastal vegetation using three-dimensional numerical calculations

DOI: 10.57757/IUGG23-2287 - LINK

Mei Yoshida[1], *Taro Arikawa*[1]
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The tsunami attenuation effect by coastal vegetation, such as mangroves, called green infrastructure, is widely known through field surveys of disasters and has been studied experimentally and numerically. Previous studies have investigated wave attenuation effects using two-dimensional numerical calculations. However, three-dimensional numerical calculations are necessary to model various wave conditions, including surf zones. Moreover, mangrove prop root shapes are complex and require small grid sizes for detailed reproduction. In addition, the resistance calculation depends on the grid size in the previous method, and applying this method to field calculations incurs high computational costs. Therefore, CADMAS-SURF/3D was employed in this study to reproduce and model mangrove forests as porous structures, and the Dupuit-Forchheimer (DF) law, whose resistance calculation is independent of grid size, was used to establish a low-cost numerical modeling method for mangrove forests. The coefficients and , which depend on the constituent materials of the porous structure, were obtained by sensitivity analysis. When =1000 and =1.0, the wave height attenuation effect is replicated with relatively good accuracy, regardless of the grid size resolution, by a calculation process reproducing the physical experiment. The relationship between the mangrove shore width and the attenuation effect was verified by three-dimensional numerical field calculations to confirm the validity and generality of the model. Upon establishment, this modeling method can evaluate the effects by of coastal vegetation on disaster attenuation in detail on a large scale.

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JS01 - Posters - Cryoseismology (IASPEI, IACS, IAG)

Cryoseismicity triggered by ice mass discharge through the Antarctic subglacial hydrographic network

DOI: 10.57757/IUGG23-3899 - LINK

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[3]*Università Roma Tre, Dip. Scienze, Roma, Italy*

We analyze seismic time series collected during experimental campaigns in the area of the David Glacier, South Victoria Land, Antarctica, between 2003 and 2016. We observe hundreds of repeating seismic events, characterized by highly correlated waveforms (cross-correlation > 0.95), which mainly occur in the floating area between the grounding and the floating line of the ice stream. The joint analysis of seismic occurrences and observed local tide measurements shows that seismicity is not triggered by a seasonal, periodic forcing such as the ocean tide, but more likely by transient irregular impulses. We consider possible environmental processes and their impact on the coupling between the glacier flow and the brittle bedrock failure. Our results suggest that clustered and repeated seismic events may be correlated with transient episodes of mass ice discharge (observed by satellite GRACE and GRACE-FO experiments) through the subglacial hydrographic system that originates upstream of the glacier and extends to the grounding zone, lubricating the interface with the bedrock. The GRACE data reveal a mass transfer from the David Glacier catchment area towards the coast which could be consistent with an emptying/refilling of the regional subglacial hydrographic network and the subsequent acceleration of the glacier flow. Basal lubrication conditions are correlated with seismic occurrences that we locate in correspondence with the main flows toward the David Cauldron.

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JS01 - Posters - Cryoseismology (IASPEI, IACS, IAG)

Hierarchical clustering applied to icequakes observed at Langhovde Glacier in East Antarctica

DOI: 10.57757/IUGG23-1308 - LINK

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[1]Hokkaido University, Institute of Low Temperature Science, Sapporo, Japan
[2]Hokkaido University, Arctic Research Center, Sapporo, Japan

Glacier often generates similar icequakes due to their common seismogenesis. Therefore, finding clusters of icequakes is critical to investigate the mechanisms of ice fracturing and glacier dynamics. We monitored icequakes near the ice-shelf front of Langhovde Glacier in East Antarctica in the summer of 2017/18 and up the grounding line of the glacier in the summer of 2021/22. The hierarchical clustering method was applied to the seismic records, which is based on the correlation coefficient among the icequakes. Seven and six clusters were generated for the seismic records in 2017/18 and 2021/22, respectively. For example, in 2017/18, clusters 1 and 2, with a center frequency of around 10 Hz, coincided with the lowering tide when the horizontal speed of the glacier increased. Clusters 3 and 4, with center frequency ranges from 20 to 50 Hz, coincided with the rising tide when the ice shelf lifted in pace with the tide. Other clusters 5-7, dominated by frequencies higher than 100 Hz, showed a relation with meteorological records. When air temperature dropped below zero, the frequencies of clusters 5 and 7 increased up to 200 events/hour. Noise generation due to high wind speed is expected to cause cluster 6. In the presentation, we will discuss the clustering method, temporal variation of the clustered events and their possible mechanisms.

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JS01 - Posters - Cryoseismology (IASPEI, IACS, IAG)

The Alaska Geophysics Network: publicly-available cross-disciplinary data covering Alaska, USA

DOI: 10.57757/IUGG23-4555 - LINK

Joanne Heslop[1], Michael West[1], Natalia Ruppert[1], Heather McFarlin[1], Stephen Holtkamp[1], Nate Murphy[1], Martin Stuefer[2], Matt Gardine[1], Dmitry Nicolsky[2], Elena Suleimani[1], n/a The Alaska Earthquake Center[1]
[1]University of Alaska, Alaska Earthquake Center, Fairbanks, USA
[2]University of Alaska, Geophysical Institute, Fairbanks, USA

Questions addressing Arctic change span earthquakes, meteorology, climate, sea ice, glaciers, permafrost, and wildfire. Many change-based research questions require consistent and continuous long-term data. By co-locating a wide variety of geophysical instruments, the Alaska Geophysics Network lends itself to enhancing cross-disciplinary research. Our stations co-locate: a 3-component broadband seismometer (Nanometrics T120PH or Kinemetrics STS-4B/5A); a Vaisala WXT weather station; a MEMS state-of-health barometer; a NCPA infrasound sensor; a SETRA microbarograph; and an Onset HOBO soil temperature profile. The stations were originally part of 192 multi-sensor platforms installed across Alaska between 2014 and 2017 by the USArray seismic project, managed by the Incorporated Research Institutions for Seismology (IRIS) as part of the NSF EarthScope program. These stations vastly expanded the amount of data available in Alaska and marked the first time seismic instruments were installed in some remote locations. Following the commencement of the USArray project, the Alaska Earthquake Center adopted the best-performing stations to become part of our permanent monitoring network. Data collected by the Alaska Geophysics Network can help explore questions related to climate, earthquakes, landslides, glaciers, sea ice, weather, wildfire, and more. All data is available for public use. In this presentation, we show the extent of the network and data and examples of cross-disciplinary cryoseismology findings from the Alaska Earthquake Center using this data.

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JS01 - Posters - Cryoseismology (IASPEI, IACS, IAG)

Iceberg Calving in Greenland: Understanding the Dynamics through Seismic Data Analysis and Machine Learning

DOI: 10.57757/IUGG23-2510 - LINK

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[2]Université de Strasbourg, Institut Terre et Environnement de Strasbourg, Strasbourg, France

The Greenland ice sheet is a critical component of the global climate system, and its significant mass loss due to iceberg-calving has greatly contributed to sea-level rise.

Through the quantification of the spatio-temporal changes in Greenland's ice mass loss resulting from iceberg calving, we gain a deeper understanding of the impact of climate change.

The mass loss related to calving icebergs can be estimated by combining mechanical simulation of iceberg calving and inversion of seismic data. Indeed, seismic signals are generated by the time-varying force produced during iceberg calving on marine-terminating glacier termini. Those events, known as glacial earthquakes, are recorded by the Greenland Ice Sheet Monitoring Network at tens of km from the source. However, differentiating these signals from tectonic events, anthropogenic noise, and other natural noise is challenging due to their wide frequency range. To overcome this challenge, we use a detection algorithm based on the STA/LTA method and machine learning (Random Forests) trained on catalogues with known events. This algorithm will be applied to continuous data to detect new and possibly smaller events. As a result, we will present a comprehensive catalogue spanning several years and discuss its relevance and reliability. Finally, we will examine the correlations between events in the catalogue and external factors, such as climatic and meteorological events. The catalogue and machine learning approach can be used in the future to extract properties of the source from the generated seismic signals, such as the volume or the shape of the iceberg.

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Predicting seasonal oscillations in daily GNSS displacement time series from geophysical fluid loading data using deep learning

DOI: 10.57757/IUGG23-1764 - LINK

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[2]*GFZ German Research Centre for Geosciences, Earth System Modelling, Potsdam, Germany*

Seasonal oscillations in GNSS time series are a major source of noise for the interpretation of tectonic signals. While some success in isolating the seasonal signals has been demonstrated with Kalman filters and matrix factorization, seasonal signals are still generally difficult to remove, especially for time series with interannually varying amplitudes.
We develop a deep learning model with the aim of predicting seasonal oscillations in GNSS time series from Earth system models describing geophysical fluid loading on the Earth's surface (developed at ESM-GFZ) and that consist of hydrological loading, and non-tidal atmospheric and oceanic loading. For our algorithm, we use globally distributed daily PPP GNSS displacement time series from Nevada Geodetic Laboratory (NGL) and isolate the seasonal displacement signals as our learning targets. We pair each target sample with a sequence of loading grids within a set time window around the sample time and spatially constrain the grids to a small area around the respective station. We test different architectures: a 3D U-Net (also called V-Net) and a time distributed LSTM-2D-ConvNet.
Finally, we evaluate the performance of our model on a hold-out data set not used during training to assess the effectiveness of our deep learning method for removing annual and semi-annual oscillations from GNSS displacement time series. We also demonstrate the effect of removing seasonals on the identification of tectonic transients, using time series from active fault zones.

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JS02 - Posters - Seismo – Geodesy (IASPEI, IAG)

Coseismic and postseismic slip observed on the Cerro Prieto Basin faults caused by the M7.2 El Mayor-Cucapah 2010 earthquake

DOI: 10.57757/IUGG23-3001 - LINK

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[1]CICESE, Seismology, Ensenada, Mexico
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Deformation in the Cerro Prieto pull apart basin (CP) located between Cerro Prieto and Imperial faults on the Mexican part of San Andreas System was studied for years. Leveling was realized in the basin by different agencies since 60’s, DInSAR analisis and GPS observations were realized many times since 1997. Since the subsidence caused by geothermal water extraction in the Cerro Prieto Geothermal Field affected the faults in the basin subsequently geotechnical instruments were installed for continuous monitoring.

The creep and episodic slip were observed on the basin faults before the 2010 earthquake. When the M7.2 EMC strikes all the geotechnical instruments, installed on the CP faults, recorded displacements triggered by the earthquake. However, the post-seismic behavior of the records varies, and 3 typical behaviors can be distinguished: 1) the creeping has similar magnitude before and after the earthquake, 2) the deformation rate after the earthquake increases and 3) the cessation of creep on the fault for up to 6 years after which the creep reactivated with a magnitude similar to that before the earthquake.

Applying an empirical relationship between magnitude and stress, the accelerometer data and Coulomb 3 modeling, we found that the dynamic stress is responsible for the triggering.

For post-seismic behavior, the Coulomb static stress changes caused by the EMC earthquake, by tectonic stresses and by fluid extraction in the Cerro Prieto geothermal field are analyzed. It can be concluded that the EMC shadow is causing creeping cessation on the faults closest to the epicenter.

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JS02 - Posters - Seismo – Geodesy (IASPEI, IAG)

Data assimilation for reproducing and predicting the fault slip behavior in the 2010 Bungo Channel long-term slow slip event

DOI: 10.57757/IUGG23-0403 - LINK

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Data assimilation (DA) is the technique to combine the observations and physics-based simulations. DA has now been widely adopted in the field of meteorology and oceanology, especially in its practical use such as weather forecast. It has recently been applied to the problem of fault slip estimation. For example, Kano et al. (2020) developed an adjoint DA method and applied to the postseismic crustal deformation data following the 2003 Tokachi-oki earthquake. They assimilated GNSS data for 15 days following the mainshock to optimize frictional properties of the afterslip area, and then examined the short-term predictability of GNSS data for the following 15 days. Hirahara and Nishikiori (2019, hereafter, HN19) proposed Ensemble Kalman Filter method and investigated the feasibility for estimating the fault slips during slow slip events (SSEs) through numerical experiments.

Following these studies, we attempt to assimilate GNSS data including long-term SSE (LSSE) in the Bungo Channel, southwest Japan, occurred during 2009-2011.We used the same fault model as HN19 covering the Bungo Channel LSSE area, consisting of one large circular patch allowing for the occurrence of SSE within the surrounding stable sliding region. By assigning the conditionally stable frictional properties, HN19 reproduced recurrent LSSEs with a similar recurrence interval, duration, and maximum slip velocity observed in the Bungo Channel LSSEs. Assuming these frictional properties as the initial model, we attempt to optimize the frictional properties in the LSSE patch by DA, and discuss the reproducibility and predictability of GNSS data.

Data assimilation (DA) is the technique to combine the observations and physics-based simulations. DA has now been widely adopted in the field of meteorology and oceanology, especially in its practical use such as weather forecast. It has recently been applied to the problem of fault slip estimation. For example, Kano et al. (2020) developed an adjoint DA method and applied to the postseismic crustal deformation data following the 2003 Tokachi-oki earthquake. They assimilated GNSS data for 15 days following the mainshock to optimize frictional properties of the afterslip area, and then examined the short-term predictability of GNSS data for the following 15 days. Hirahara and Nishikiori (2019, hereafter, HN19) proposed Ensemble Kalman Filter method and investigated the feasibility for estimating the fault slips during slow slip events (SSEs) through numerical experiments.

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JS02 - Posters - Seismo – Geodesy (IASPEI, IAG)

Distribution, duration and size of slow-slip events in the eastern Mediterranean: Insights from the Hellenic subduction system

DOI: 10.57757/IUGG23-1776 - [LINK]

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[2]National Observatory of Athens, Institute of Geodynamics, Athens, Greece
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[6]Ruhr University Bochum, Institute of Geology- Mineralogy and Geophysics, Bochum, Germany
[7]GFZ, Department of Geosystems, Potsdam, Germany
[8]Technical University of Crete, School of Mineral Resources Engineering, Chania, Greece

Slow-slip events (SSEs), although widely recorded in various convergent margins globally, only recently have been reported in the Eastern Mediterranean, with one of them triggering the 2018 ~M7 Zakynthos Earthquake along the western Hellenic Subduction System (HSS). Here, we explore the distribution, size and duration of SSEs along the HSS and assess their importance in subduction-related strain accumulation and release. To achieve this, we analyse geodetic timeseries from a dense network of permanent GNSS stations on Western Peloponnese, Crete and surrounding islands that collectively span a time-period of ~10 years. We use greedy linear regression techniques to estimate displacement trajectory models for each station and thus we identify transient displacement signals, associated with aseismic processes at depth. To further constrain the spatial extent and size of the SSEs we invert the GNSS transient displacements for variable distributed slip at depth and we, therefore, discuss likely scenarios of aseismic and seismic strain distribution (and partitioning) within the HSS's complex plate-interface zone.

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JS02 - Posters - Seismo – Geodesy (IASPEI, IAG)

Simultaneous estimation of the spatio-temporal evolution of fault slip and block motion in the southwest Japan subduction zone

DOI: 10.57757/IUGG23-2542 - [LINK]

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Department of Statistical Inference and Mathematics, Tokyo- Tachikawa, Japan

Interseismic deformation in a plate subduction zone is attributed to not only slip and coupling on the plate boundary but also strain partitioning on overriding plates. The latter is often modeled by rigid motion of small tectonic blocks and slip on their boundary faults. Although many deformation analyses for southwest Japan have revealed spatio-temporal distribution of these phenomena, their interaction and the effect on the total slip budget is a remaining important topic. This is because previous studies individually analyzed different areas and periods using different estimation methods, making us difficult to combine their results. Therefore, we attempt a comprehensive estimation of the spatio-temporal evolution of interplate slip and block motion around southwest Japan based on state space modeling, using GNSS time series for about 25 years. Toward this final goal, we first evaluated separation precision between fault slip and block motion by numerical experiment. We generated synthetic displacement time series for 770 GNSS sites around southwest Japan assuming various contribution ratios for interplate back slip and block motion of the forearc region. Then, we applied the formulation of block modeling suggested by Meade and Loveless (2009) to Kalman filtering. As a result, cumulative back slip on the plate interface always showed underestimation of about 10 to 40 % for known strongly coupled regions beneath the Tonankai and Shikoku regions. Correspondingly, block motion showed slight overestimation. In the presentation, we will discuss the detailed structure and mechanism of the trade-off between unknown parameters through covariance matrix estimated by Kalman filtering.

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JS02 - Posters - Seismo – Geodesy (IASPEI, IAG)

The relationship between background seismicity rate and strain rate in and around the strain concentration zones in Japan

DOI: 10.57757/IUGG23-2221 - LINK

Taku Ueda[1], Takuya Nishimura[1]
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Earthquakes are caused by the stress accumulation in the earth's interior due to the relative plate motion. Therefore, it is considered that the geodetically-estimated strain rate may correlate with seismicity, and this relationship has been discussed in several areas in the world (e.g., Zeng et al., 2018). In this study, we investigate the spatial correlation between the strain rate and the background seismicity for crustal seismicity in Japan.

We applied the Hierarchical Space-Time Epidemic Type Aftershock Sequence (HIST-ETAS) model (e.g., Ogata, 2004) to the M > 3.0 crustal earthquakes (JMA catalog, 1980-2010, depth < 25km). We evaluated background seismicity using the estimated HIST-ETAS parameters and compared it with the strain rate estimated using the GNSS data (1997-1999 and 2006-2009) by Fukahata et al. (2022). The study regions are in and around the four strain concentration zones: the Niigata Kobe Tectonic Zone (NKTZ), the Ou Backbone Range (OBR), the San-in shear zone (SSZ), and the Beppu-Shimabara graben (BSG).

We found spatial variations in background seismicity in and around the NKTZ and the OBR positively correlate with that in the strain rate. No significant correlation was found in and around the SSZ and the BSG. It is possible that the results could be improved by appropriately removing deformations attributed to interplate coupling and non-tectonic local deformations.

Acknowledgements: The JMA catalog was used; the code of Ogata et al. (2021) was used to estimate parameters of the HIST-ETAS model. I thank T. Okazaki for providing strain rate data (Fukahata et al., 2022).

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JS02 - Posters - Seismo – Geodesy (IASPEI, IAG)

Comparison of long period passive seismic and gravity measurements on the island Heligoland in the German Bight (North Sea)

DOI: 10.57757/IUGG23-3349 - [LINK]

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Digital broad-band seismic recordings from station HLG on the small island of Heligoland in the German Bight in the North Sea are available since 2001. Since July 2017, an additional local network of six broad-band seismometers is operational on Heligoland with a focus on investigations of local microseism in the North Sea.
In this study, we combine information gathered by passive seismic registration and gravity measurements from a superconducting gravimeter on Heligoland. We utilize 20 years of passive seismic data for long period spectral investigations spanning periods of tens of seconds up to several years. In the period band between 70 to 100 s, H/V ratios reveal strong noise on the horizontal components occurring contemporaneously with strong storms. In addition, distinct peaks in the spectral data are observed at periods of 6, 12 and 24 hours, which can be related to ocean tides and atmospheric pressure variations that are affecting the amplitude of local microseism. We compare the spectral seismic data with three years of gravity spectra from a collocated superconducting gravimeter. They are highly comparable with the seismic spectra and show distinct differences between local tides in the North Sea and solid Earth tides.
At even longer periods up to several years, the spectral seismic data reveal a strong signal at one year, accompanied by peaks at 0.5, 2, 3 and 8 years. These variations seem to affect mostly the secondary microseism of the Northern Atlantic recorded at station HLG.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Adjoint-state traveltime tomography in Central Java enhanced by a machine-learning-assisted catalog

DOI: 10.57757/IUGG23-3791 - LINK

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[1]*Nanyang Technological University, School of Physical and Mathematical Sciences, Singapore, Singapore*
[2]*National Research and Innovation Agency of Indonesia BRIN, Research Center for Geological Disaster, Bandung, Indonesia*
[3]*Institute of Geology and Geophysics- Chinese Academy of Sciences, Key Laboratory of Earth and Planetary Physics, Beijing, China*
[4]*Nanyang Technological University, Earth Observatory of Singapore, Singapore, Singapore*
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As one of the most populous regions, Central Java in Indonesia is prone to high seismic and volcanic hazards, primarily due to the progressive northward subduction of the Australian plate beneath the Sunda plate. Detailed velocity structure of the crust and uppermost mantle beneath Central Java is critical for an improved understanding of the subduction processes and the associated seismicity and volcanism. Despite several independent isotropic velocity models proposed for the region, crustal-scale anisotropic structure, which reflects past and ongoing deformation, has rarely been investigated. Our goal is to image the crustal-scale P-wave azimuthally anisotropic structure beneath Central Java. Seismic data used were recorded by > 200 seismic stations from multiple projects. To make full use of the open access data, machine learning phase picking and subsequent event association and location were applied to build a local earthquake catalog. The machine-learning-based workflow detects > 1000 events, roughly triple the amount from previous manual picking. Notably, the preliminary catalog includes a large number of earthquakes that were located in the offshore areas but were recorded by land stations to the north, resulting in huge back azimuthal gaps and potential bias in earthquake relocation. The ongoing study attempts to involve depth phases, such as sPn and sPg, for more accurate earthquake locations and thus more reliable tomographic images. With the expanded and refined seismicity catalog, a ray-free adjoint-state traveltime tomography package called TomoATT will be used for the 3-D velocity heterogeneity and azimuthal anisotropy beneath Central Java.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Multiscale analysis of the GOCE signal in the subduction zones

DOI: 10.57757/IUGG23-2420 - LINK

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Owing to space gravity missions, unprecedented high-quality data are now available on the entire Earth surface. In particular, the GOCE mission allows the study of features as small as 80 km in subduction systems, often characterized by a sparse spatial coverage of available ground gravity data. Providing unique information on the mass distribution, these data coupled with seismological and topographic measurements can allow a major advance in the characterization of the geometry and thermal structure of the subducting plate which play an essential role in the distribution of seismicity. The analysis of the associated signal will, however, highly depend on our ability to separate the components related to the superficial structures (< 200 km depth) from the ones at depth in the total signal. In this work, we attempt to evaluate the crust and lithosphere contributions at the surface in the GOCE data by calculating the gravity signature (geoid, gravity disturbance and gravity gradients) of synthetic slabs derived from geodynamical models varying lithospheric plate ages and crust characteristics. A continuous wavelet transform (CWT) is then applied to the synthetic and observed signals. Such analysis allows us to unfold their components and finely characterize their local features at different spatial scales. We will show that this approach, combining different gravity signal components and CWT, is particularly well suited to estimate the different signal contributions in the subduction zones, which are characterized by a superimposition of structures on a broad range of scales.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Determination of the seismic structure of the Earth's mantle based on joint analysis of gravimetric and seismometric data

DOI: 10.57757/IUGG23-3564 - LINK

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[1]Institute of Geodesy and Cartography, Center of Geodesy and Geodynamics, Warsaw, Poland
[2]Polish Geological Institute – National Research Institute, Geohazards Center, Warsaw, Poland
[3]Accenture, Applied Intelligence, San Francisco, USA

This study presents a new concept of joint analysis of the gravimetric and seismometric recordings of earthquakes for determining the seismic structure of the Earth's mantle. The proposed method allows using gravimetric data without the known full transfer function of the instrument. Group and phase velocity dispersion curves of the fundamental mode of Rayleigh waves are measured from recordings of superconducting gravimeter and broad-band seismometers operating at the same location, allowing for exploration of a broader response for incoming seismic waves. The analysed sites, the Yebes, Larzac, Wettzell, Pecny and Borowa Góra Observatories, are located along the profile going from central Spain to central Poland and crossing the main tectonic unite of Europe – the Trans-European Suture Zone. Calculated dispersion curves are inverted by the weighted linear inversion and Monte Carlo methods to estimate a distribution of shear-wave seismic velocity in the Earth's mantle. A comparison of the deterministic and probabilistic inversion methods can excellently demonstrate surface waves' ability to determine the Earth's mantle structure.

This work was done within the research project No. 2017/27/B/ST10/01600 financed from the Polish National Science Centre funds.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The electromagnetic signature of the Moldanubian-Saxothuringian boundary

DOI: 10.57757/IUGG23-2502 - [LINK]

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The Moldanubian-Saxothuringian boundary is one of the major suture zones within the Variscan orogen. It formed in the Paleozoic during the collision of Laurentia and Gondwana and the two distinct units have been either interpreted as remnants of microcontinents or as a sequence of large-scale nappes. The Moldanubian-Saxothuringian boundary has been studied and identified in exposed parts of the Variscan in the Bohemian Massif and Schwarzwald-Voges area. However, its exact location below Mesozoic cover in other areas is still enigmatic. Due to the lack of outcrop and well data magnetic and gravity data have been utilized in locating this interface in the subsurface.

Previous magnetotelluric experiments have largely concentrated on the Bohemian Massif around the KTB and the Eger Rift. This region has also been the target of seismological investigations. Further south-west in central Bavaria only potential field data and scattered magnetotelluric measurements are currently available. However, even in combination these are not sufficient to clarify the geometry of the suture, the depth extent of boundary faults and other first order parameters. To provide further constraints on this, we collected long-period magnetotelluric measurements across the suspected boundary region. Here we show first results from remote-reference data processing of these new data and how they agree with the inferred resistivity structure from a large-scale 3D resistivity model of Germany.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Improving tomographic models of the Pyrenees region (NE Iberia): Preliminary results from Full-Waveform Inversion

DOI: 10.57757/IUGG23-3257 - LINK

Paula Herrero-Barbero[1], Mario Ruiz[1], Jordi Diaz[1], Christian Boehm[2], Pienkowska Marta[3], Josep de la Puente[4], Arnau Folch[1], Ramon Carbonell[1]
[1]Geosciences Barcelona, Geo3Bcn-CSIC, Barcelona, Spain
[2]Mondaic, Mondaic, Zurich, Switzerland
[3]ETH Zurich, Department of Earth Sciences, Zurich, Switzerland
[4]Barcelona Supercomputing Center BSC, Barcelona Supercomputing Center BSC, Barcelona, Spain

Detailed imaging of subsurface crustal structures requires inverse modeling from massive amounts of waveform data, including regional and/or local seismic events of lower magnitudes and high frequencies, aspects not conventionally used in Full-Waveform Inversion (FWI). The use of higher frequency signals notably boosts spatial model resolution but increases the computational cost of inversion, affordable only with HPC infrastructures. Preliminary tomographic models for the Eastern Pyrenees region have been constrained through a visco-elastic FWI using seismic data. Three-component recordings were provided by over 120 stations from a high-density seismic deployment. To optimize coverage, in addition to the far-field waveforms from M>4.5 events, data from 23 smaller magnitude earthquakes were included from a temporary broad-band seismic network deployed between September 2019 and November 2020. Moment tensor solutions of these additional seismic data were determined, and the seismograms were bandpass filtered. Through this computationally intensive workflow, multiple iterations resulted in a better fit with the observed seismograms, and point to improved spatial resolution of shallow structures. This contribution, aims to disclose and discuss the difficulties and challenges faced when using relatively high frequency seismic recordings in visco-elastic FWI applications, as well as addressing the benefits of the resulting models. Improved tomographic models could be the basis for more accurate waveform modeling and we hope that they will contribute to improve ground-motion simulations on a regional scale. This research is funded and contributes to the objectives of the Horizon Europe Project DT-GEO: A Digital Twin for GEOphysical extremes (ID 101058129).

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Magnetic properties of Precambrian rocks from the Denman Glacier area and the Obruchev Hills

DOI: 10.57757/IUGG23-1629 - LINK

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This study covered an area on the western side of the Denman Glacier and the Obruchev Hills, where the predominantly granulite-facies metamorphic rocks exposed of rather different composition. They are intruded by a wide variety of plutonic rocks, including a major batholith of syenitic to granitic composition at David Island.

A variety of intrusive rocks (gabbrodiorite, granite-aplite and Bt-granite) of 500 m.a. batholith, exposed at Cape Delay Point, are characterized by high values of magnetic susceptibility $(13\div22)\times10^{-3}$ SI units. However, biotite gabbro has low values. The granosyenites and granodiorites of Hippo Island mainly have high values of magnetic susceptibility $(40\div50)\times10^{-3}$ SI units. The Batholith dyke complex in the area of Cape Kennedy is mainly composed by non-magnetic rocks, with the exception of Bt leucogranite 64×10^{-3} SI units. Also, the aplite of Gilles Island has high values of magnetic susceptibility $(55\div70)\times10^{-3}$ SI units.

The Archean Cape Charcot metamorphic rocks include weakly magnetic paragneisses $(4\div5)\times10^{-3}$ SI units and non-magnetic orthogneisses $\sim0.3\times10^{-3}$ SI units. Metamorphic rocks of the Davis Peninsula basement are characterized by values of $(0.05\div9)\times10^{-3}$ SI units and are represented by Amf-Bt orthogneisses and banded gneisses. Thus, the main sources of anomalies in the studied area are intrusive rocks of batholith, while Archean crystalline basement only forms a common magnetic background. The magnetic rocks of the Obruchev Hills and Cape Jones are represented by (±Px)-Amf-Bt orthogneisses $(30\div90)\times10^{-3}$ SI units, which form the main anomaly magnetic field pattern. Magnetic susceptibility values for Sill-Bt and Grt-Bt paragneisses do not exceed 0.4×10^{-3} SI units.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Crust and upper mantle conductivity models of the western Ukrainian Shield and their link to tectonic structure and mineralization

DOI: 10.57757/IUGG23-1947 - LINK

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[2]Institute of Geophysics- National Academy of Sciences of Ukraine, Tectonosphere, Kyiv, Ukraine

A dense network of long-period magnetotelluric and magnetovariational data in the period range of 3-16 to 2500-3600s made it possible to explore the geoelectrical structure of the western part of the Ukrainian Shield limited by coordinates 26°-30°E and 48°- 51,7°N. 3D inversion resulted in the creation of spatial models of electrical conductivity for the territory of investigation. The local character of the conductors and their position indicate their connection with recently activated fault zones, their junctions and with metallogeny. The Precambrian age of crystalline rocks of the investigated area refers mainly to the electronic-type graphite-sulphite origin of increased conductivity, however the depth of conductive features, their vertical extent and their link to rejuvenated fault systems may indicate the genetic connection of various minerals and their subsequent precipitation with deep fluid migration. The obtained results correlated with heat flow data are aimed at clarifying the deep structure and linking the geoelectric features of the earth's crust and upper mantle with fault systems and deposits of various natural mineral sources and can serve as evidence of tectonic processes in the studied area.

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Data-driven thermomechanical state of the Alpine Himalayan Collision Zone: implications for continental dynamics

DOI: 10.57757/IUGG23-4329 - LINK

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We study the present-day thermomechanical state of the Alpine Himalayan Collision Zone lithosphere using data-driven modelling, to understand the physics controlling the observed crustal differentiation and the underlying continental dynamics. We found that there exists thermodynamically (internal energy, chemical composition) controlled critical crustal thickness, which is close to the global average of the continental crust. The regions with thickness higher than the critical thickness, i.e. orogenic lithospheres, have higher potential energy acquired from the tectonic forces and are rendered weak by the internal energy from the heat-producing elements, compared to the continental interior lithospheres that have crustal thickness close to the critical crustal thickness. The weaker orogenic lithospheres are deforming in dissipative mode to release the acquired potential energy, which manifests as zones of diffused deformation. Further, we find that the energy dissipation path taken by orogenic lithosphere to either attain critical crustal thickness or not, depends on the feedback between thermal and mechanical relaxation of the lithosphere and the internal energy in the crust. The internal energy stored in the crust from heat-producing elements helps the dissipation of the acquired potential energy to attain the critical crustal thickness.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Variations in lithospheric thickness beneath the Southern Indian Shield from joint modelling of receiver function and surface wave dispersion

DOI: 10.57757/IUGG23-2824 - LINK

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Southern Indian Shield is a mosaic of several cratonic blocks which include the Western Dharwar cratons (WDC), Eastern Dharwar cratons (EDC), Southern Granulite Terrain (SGT) and Deccan Volcanic Province (DVP). We investigated the shear wave velocity structure of the shield using joint modelling of teleseismic receiver functions and surface wave dispersion data recorded at 56 seismological stations. We analysed the data comprising waveforms of the teleseismic (epicentral distance 30–95º) earthquakes of magnitude >5.5 recorded at broadband seismic station. P-wave Receiver Functions were computed at Gaussian of width 1.0.

We estimated thickness of lithosphere in the DVP, EDC and WDC using the joint modelling of the teleseismic receiver functions and surface wave dispersion data along with teleseismic relative residuals data. The thicknesses of lithosphere are found in range of 210, 160-130 and 125 km beneath the WDC, EDC and DVP, respectively. The variation in lithospheric thickness under these different geological blocks shows different type of tectonic evaluation regime. The lithosphere, under the DVP, is modified due to Deccan volcanic event while in the WDC cratonic root is preserved and prevented from deformation due to its distinct composition. The EDC indicates modification in lithospheric thickness due to evolution of Cuddapah basin.

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Evaluating 3D models from potential fields data across oil producing blocks in pre-salt campos basin, Brazil

DOI: 10.57757/IUGG23-1211 - LINK

Emanuele La Terra[1], Sergio L. Fontes[1], Maxi A. Meju[2], Rodrigo A. Alberti[1], Gilmar V. Bueno[3], José A. Pereira[1], Miguel A. Tupinamba[4], Ali A. Hashim[5]
[1]National Observatory, Geophysics, Rio de Janeiro, Brazil
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[5]Petronas Brasil, Geophysics, Rio de Janeiro, Brazil

Three-dimensional potential fields models are being tested in the Brazilian pre-salt region of the Campos Basin, where a noticeable magnetic anomaly with oval outline was identified. The study area is relevant for tests, as 3 abandoned pioneer wells with depths varying between 5500 and 7100m were re-drilled and marked the presence of oil, one of which is a commercial producer. These wells cut through several sedimentary formations of the basin, including shales with intercalations of carbonates and sandstones. Thick layers of salt were crossed, and intercalations of volcanic and carbonates are present below the salt. Oil samples were identified at the top of a volcanic sheet at 7100m depth. Some 3D inversion models of both the magnetic susceptibility distribution and density contrast fit the observed data. To reduce the non-uniqueness of potential field models, inversions were constrained by well logs, geological and other existing geophysical data. Several parameters were considered during the inversion procedure including cell dimensions, data quantity, reference models, assigned uncertainties, depth weighting, wavelet compression of sensitivity matrix, choice of regularization parameter. A Multiphysics approach was found to facilitate the selection of the best models. The results evidenced anomalies of density and magnetic susceptibility associated with the volcanic rocks that display variations laterally and in depth and satisfactorily explains the oval magnetic anomaly.

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The OHANA OBS deployment in the Northeast Pacific Ocean

DOI: 10.57757/IUGG23-0780 - LINK

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[3]*UC Santa Cruz, Earth and Planetary Sciences Dept., Santa Cruz, USA*

In early 2023, 25 broadband ocean bottom seismometers (OBSs) were recovered in the northeast Pacific Ocean, about halfway between Hawaii and the North American west coast. These instruments had collected seismic data continuously for nearly 15 months.

The OHANA project is an integrative seismic study to explore the crust, lithosphere and asthenosphere in a 600~km wide region west of the Moonless Mountains. The new data will enhance seismic imaging in a regional as well as in a global context: regionally, the analysis of surface waves and receiver functions as well as surface wave azimuthal anisotropy and shear-wave splitting will provide insight into the seismic structure within the OBS network and mantle deformation fabric of 40-to-50 Myr old Pacific lithosphere. A fundamental question to be addressed is whether this particular area has the signature of a normal plate cooling history or if there is evidence for a previously proposed reheating process, e.g. resulting from small-scale shallow-mantle convection.

Within a global framework, the new surface wave data will profoundly improve current global dispersion maps, allowing researchers to reduce imaging biases caused by trade-offs between lateral isotropic heterogeneity and azimuthal anisotropy that result from uneven data coverage, in the study area as well as far outside of it.

The ONAHA network occupied one of the the long-envisioned locations of the Pacific Array and thereby contributes to this larger international community initiative.

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Magnetotelluric imaging of the Sulu UHP metamorphic belt between the North China and Yangtze cratons

DOI: 10.57757/IUGG23-2836 - LINK

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[1]*Guangzhou Institute of Geochemistry- Chinese Academy of Sciences, State Key Laboratory of Isotope Geochemistry, Guangzhou, China*
[2]*Institute of Geology and Geophysics- Chinese Academy of Sciences, State Key Laboratory of Lithospheric Evolution, Beijing, China*
[3]*Institute of Geology- China Earthquake Administration, State Key Laboratory of Earthquake Dynamics, Beijing, China*

The Triassic collision between the North China Craton (NCC) and Yangtze Craton (YC) created the world's largest ultrahigh-pressure (UHP) metamorphic belt (the Dabie-Sulu Orogen). Although abundant in the associated geologic records, geophysical fingerprints from oceanic subduction to continental collision and deep subduction remain largely unveiled. In 2019, broadband and long-period magnetotelluric (MT) data were collected along two parallel profiles that extend from the Subei Basin in YC, across the Sulu Orogenic Belt (SOB), and onto the eastern NCC. These data, together with available legacy MT data throughout the region, were inverted using a regularized nonlinear inversion algorithm to produce a three-dimensional electrical resistivity model. The model reveals three prominent features in the crust and upper mantle: (1) A highly resistive column extends from the surface to a depth of >100 km directly beneath the SOB, with a width closely matches the outcrop width of the UHP metamorphic rocks; (2) A narrow, elongated crustal conductor at 25–40 km depth that lies along the western edge of the SOB, which we interpreted as graphite/sulfide that was emplaced into the crust during the orogeny; and (3) A broad zone (~200 km wide) of enhanced conductivity that is centered in the middle-lower crust to upper mantle beneath the rifted eastern NCC, which is likely associated with partial melting of volatile-bearing peridotite formed by subduction-related metasomatism. These observations provide insights into the assembly of the NCC and YC, and demonstrate the promise of using the MT method to study ancient subduction/collision activities.

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The role of inheritance and kinematics in shaping the West Antarctica Rift System (WARS): A parametric study

DOI: 10.57757/IUGG23-2599 - LINK

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[2]National Institute of Oceanography and Applied Geophysics, Sgonico, Italy

Extensional tectonics in continental settings usually results in lithospheric stretching of narrow (e.g. Upper Rhine Graben), as well as wide regions (e.g. Basin and Range). Some rift systems bear evidence of a transition between the two styles: the West Antarctica Rift System (WARS) have likely progressed from diffuse to focused rifting (Cretaceous - Middle Neogene). The system currently covers a length of 1000 km, at the boundary between East and West Antarctica and is composed of four main basins (Victoria Land Basin, Central Trough, Northern Basin and Eastern Basin). The deformation pattern and available geological reconstructions suggest that, at least for some part of the rifting, the extension occurred concurrently in multiple sections.

Inheritance of prior structural, thermal, and rheological heterogeneities is likely a controlling factor in this evolution [1]. Consequently, with the goal of identifying the most likely initial conditions, we designed a series of 2-D numerical models, analysing the effect of variations in the temperature field, rheology, accumulated strain, distribution of extensional pulses on the basins' geometry. To this aim, we used the open source Underworld2 [2] and BGR-02 and ACRUP2 profiles [3], as 2-D analogue of the WARS structures in the Southern Ross Sea.

The results show that the models most consistent with the observations are those that include inherited weakness zones at the cratonic boundary. Early onset of focused extension often occurs, with high sensitivity to the pattern of inherited weakening.

[1] Perron et al. (2021). DOI:10.1051/bsgf/2020038

[2] Mansour et al. (2020). DOI:10.21105/joss.01797

[3] Trey et al. (1999). DOI:10.1016/S0040-1951(98)00155-3

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Effective elastic thickness over North East India and the Bay of Bengal using joint analysis of gravity and topography data

DOI: 10.57757/IUGG23-3107 - LINK

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The geodynamic structure of the continental Northeast India (NEI) is shaped by the collision of the Indian and the Eurasian plate in the north and subduction of the Indian plate underneath the Burmese plate in the eastward direction. The oceanic lithosphere of the Bay of Bengal (BOB) is evolved due to rifting of India and Antarctica, has been mainly affected by two aseismic ridges emplacement: Ninetyeast and 85° ridges. Effective elastic thickness (Te) of the lithosphere is an important parameter for mechanical strength which provides information about the rheology of the deformation and evolution of the lithosphere. In this study region, we have calculated Te, by applying joint inversion of the real admittance and coherency between topographic and gravity anomaly data by using PlateFlex software. Load ratio (F) has also been determined to understand the mass distribution of surface and subsurface, where low F (< 0.2) in the Northeast India and the northernmost part of BOB represent surface loads is dominated in comparison to subsurface loads, while high F in the BOB region is dominated by subsurface loading. The spatial variation of Te varies ranging between 3–55 km. Low values of Te (9–16 km) over the 85° ridge correspond mainly to high thermal structure and weak lithosphere strength while slightly high in the activated Shillong Plateau (Te ~ 30 km) which indicates high seismic activity. High Te > 40 km in the Northeastern part of the Indian shield correlates mainly with low heat flow shows strong lithospheric strength.

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3D electrical resistivity image of the Dharwar Craton, India

DOI: 10.57757/IUGG23-1396 - [LINK]

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The Archean cratons are the key to understand the crust formation, the early Earth geodynamics, and the subsequent transition to the present-day plate tectonics. Dharwar craton is a granite-gneiss-greenstone terrain, situated in the south India bounded by Deccan traps, Southern Granulite Terrain (SGT), Eastern Ghat Mobile Belts (EGMB) and Arabian Sea in north, south, east, and west respectively. The subduction-accretion (plate tectonic) models and plume-plate tectonic mixed models are proposed by various authors for the crustal evolution of the Dharwar craton. In this study, we present the 3D inversion results of magnetotelluric (MT) data from the Dharwar craton using the long period MT (LMT) measurements. The LMT data is acquired in a 3D grid fashion, covering the entire Dharwar craton. This study delivers the lateral and vertical variations in electrical resistivity of the Dharwar subsurface. The crust beneath the Dharwar craton is highly resistive in nature with few conductive zones. The conductive zones in the crust subsequently join with the upper mantle which is observed as a broad and interconnected conductive zone. Highly resistive segments that extend to the upper mantle indicates the locations of preserved lithosphere in the Dharwar craton. An anomalous conductive body is seen in the upper mantle in the north-western part of the craton. Its relations to the evolution of Dharwar craton will be discussed.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Extending Magnetotelluric Study from Central to Eastern Mongolia: Preliminary 2-D and 3-D Inversion Results

DOI: 10.57757/IUGG23-4312 - LINK

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Deformation in the continental interior, far from tectonic plate boundaries, is not fully understood. Due to its location, Mongolia is a prime natural laboratory for studying effects such as intracontinental deformation and intraplate volcanism. A previous regional magnetotelluric (MT) study, including three (2016-2018) field campaigns, identified a localized asthenospheric upwelling with a correspondingly thin lithosphere underneath the Hangai Dome (Central Mongolia).

Compared with Central Mongolia, Eastern Mongolia is less studied with geophysical methods; consequently, its underlying lithospheric and asthenospheric properties are less constrained. At the same time, this region is of economic and scientific interest, as it hosts several mineral zones and relevant geological features, such as the Mongolia-Okhotsk suture zone. Furthermore, it is unknown to what extent the identified electrical conductivity anomalies in Central Mongolia extend to the east and how the crust and mantle differ in this region.

This work presents the first results of a new MT field study covering Central-Eastern Mongolia. 64 broadband MT stations were deployed between 2020 and 2022 along five profiles east of the Hangai. The data were processed using a two-step multi-taper processing approach, simultaneously improving the quality at short and long periods, providing credible MT responses up to 2048 seconds. The previously acquired and new data were jointly inverted regarding 3-D conductivity variations. Furthermore, data from an 880 km long 2-D profile extending from the Selenga Basin to Gobi Desert were inverted independently. This study is part of a broader project aiming to constrain the electrical conductivity of entire Mongolia.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Deployment of a regional scale magnetotelluric (MT) array in the Pannonian Basin

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In the framework of the Pannon LitH_2Oscope Lendület project in Hungary, we investigated the lithosphere structure of the Pannonian Basin. Besides seismological and geochemical methods, a large-scale grid of MT stations was used for an in-depth investigation of the sedimentary basins. The aim of the group is to explain how the thinner-than-average continental lithosphere could have formed and what is the role of fluids. The theory that discusses the effect of fluids on the melting relations and rheology of the lithosphere and upper mantle is called the pargasosphere hypothesis. For the MT part of the study, aimed at imaging the well conductive layer at the base of the lithosphere, 38 soundings were implemented close to the broad-band seismological stations, achieving a nearly uniform MT coverage in the Pannonian Basin.

Our goal was to achieve as accurate as possible mapping of the lithosphere-asthenosphere boundary (LAB) from the MT data. In the MT modeling and inversion, we have considered resistivity profiles calculated from geochemical data, providing an estimate for the rock compositions and fluid contents assumed to be present in the lower crust and upper mantle. Therefore, MT modeling provides a simple approach to test these geochemical assumptions. Furthermore, the new MT data were also suitable for mapping the resistivity distribution of the deep structure of the Pannonian Basin more accurately than ever before. In the 1D and 3D MT modeling, we also incorporated some available a priori datasets into the models. In this work, we present some selected preliminary MT results.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Lateral variation of the Main Himalayan Thrust in the north-western Himalayas retrieved from Magnetotelluric 3D forward modelling

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Understanding the arc parallel variation on the geometry of the Main Himalayan Thrust (MHT) is as much important as the arc perpendicular variation in the collision tectonics such as Himalayas. Geometrical variation of the MHT has a significant role on the occurrence of major/great earthquake. The lateral variation in the geometry of the MHT beneath the north-western Himalayas is studied to understand the crustal structure from the magnetotelluric (MT) 3D forward modelling. We computed MT impedance tensors from 3D forward modelling algorithm MTD3FWD, which computes magnetic and electric fields at the surface of a 3D electrical resistivity model illuminated by electromagnetic plane waves. The previous resistivity and velocity models in different sectors of the north-western Himalayas are utilized as inputs to create a 3D model. The mapped MHT shows a lateral ramp on the Garhwal and Kumaun sectors of north-western Himalayas. The crustal structure of this region has segmented by nearly vertical resistive and conductive tectonic features beneath the Himachal and Garhwal-Kumaun region. These tectonic features are interpreted as the continuation of Delhi Haridwar Ridge and Great Boundary fault, respectively. These subsurface structures plays major role on controlling ongoing seismicity in this region.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

2-D and 3-D inversion: A case study from the Deccan Volcanic Province and the western Dharwar craton, India

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We attempted a comparison of the crustal electrical conductivity structure deduced by two-dimensional (2-D) and three-dimensional (3-D) magnetotelluric inversion for data obtained at 19 stations spanning a profile length of about 150 km. Station spacing is 10-15 km. A non-linear conjugate gradient scheme is used for 2-D inversion for both apparent resistivity and phase. Several conductive features are mapped in the 2-D model. This study shows the upper crust is highly resistive (>10,000 ohm-m) all along the profile. It suggests the presence of the tonalite-trondhjemite-granodiorite (TTG) crust. The conductor mapped on the NW part of the profile is considered a deep-seated fault representing a boundary or a rift-related feature beneath the Deccan Volcanic Province and the western Dharwar craton. This conducting feature can be interpreted as an extension of the Kaladgi basin further west. On the central and SE sides of the profile, the mid-crust shows a highly resistive nature. The sensitivity analyses confirm the robustness of the conductive features obtained in the 2-D models. 3-D inversion was carried out by ModEM code with data of the diagonal and off-diagonal components. 2-D and 3-D resistivity models are compared. Finally, the electrical resistivity nature of the crust is compared with other shield and rift regions of the world.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Crustal and upper mantle structure beneath Corinth rift

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In this study, we use P wave receiver functions from teleseismic events recorded at 24 permanent stations in the Corinth Rift and the surrounding regions to determine the crustal structures (thickness and Vp/Vs ratio) and the African slab geometry. Stations are operated by the National Network of Greece and are equipped with broadband seismometers. We selected events recorded between 2011 and 2021 with magnitude > 6.0 and epicentral distances between 30 and 95 degrees. We computed the receiver functions for each station using iterative time deconvolution and used Zhu and Kanamori's stacking method (2000) to estimate crustal thickness and Vp/Vs ratio. The results show that Moho depth varies from 28 km (Eastern Corinth rift) to 45 km in the western studied area. The deeper Moho values are correlated with the Hellenides mountain range (western part) and an isostatic behaviour. Some stations at the eastern Corinth rift (LOUT, LTK, PROD, KLV, GUR, VILL) display a clear signature from the subducting African crust, allowing for a better estimate of its thickness variation and lateral geometry changes. Arrival times and polarities of P to S converted waves at dipping structures are sensitive to the incident angle of the teleseismic P wave. For stations having good azimuthal coverage, the geometry (dip direction and dip value) of the slab crust and/or of the Aegean Moho beneath the stations will thus be inferred by inversion of the data through a grid search.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

Gravimetric signature of subduction zones deep thermal structures.

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At subduction zones, cold lithospheric plates dive deep into the hotter Earth's mantle. Earthquakes can occur at depths of hundreds of kilometers in these cold subducted slabs, apparently related to their thermal structures. Seismic tomography provides a first-order information on slab morphology but cannot discriminate « cold » from « warm » slabs due to the inhomogeneous repartition of seismic sources and surface sensors. This study investigates the potential of the gravity data from the GOCE mission to infer slabs' inner thermal structures. Deep thermal structures (> 200 km depth) are derived from dynamic subduction zones models or from simplified analytical structures (ellipsoidal shape). Our parametric study considers various dip angles, morphologies, slab core temperatures, radial and axial thermal gradients. We convert temperature field into density and use the freeware DynG3 (Cadio et al. 2011) to predict surface and CMB deflections due to slab dynamic sinking, depending on the radial mantle viscosity, and calculate the corresponding synthetic signals (geoid, gravity disturbance, gravity gradients). As expected, they are sensitive to density anomalies at different depth ranges. Geoid anomalies reflect deep anomalies (> 600 km depth), whereas gradiometric anomalies mostly represent anomalies in the upper mantle. We also perform a sensitivity study of gravimetic signals for the same realistic slab morphology (e.g. piled, deflected) exhibiting various slab core temperatures. Variations between different inner thermal structures are greater than the detection threshold of the GOCE sensors. These preliminary results are encouraging to later infer subduction zones deep thermal structures from GOCE data.

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JS03 - Posters - Probing the Earth's Lithosphere: Understanding Tectonic, Volcanic, Cryotonic and Geodynamic Processes Using Geophysical Methods (IASPEI, IAG, IAGA)

The Northern Zagros orogenic belt tectonics examined by Magnetotellurics

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The collision of the Arabian and Eurasian plates during the early Miocene resulted in the formation of the Zagros mountain belt, which extends from northwest to southeast across the western half of Iran. This area is of significant geological and tectonic interest due to its complex history and ongoing deformation. Recently, Magnetotelluric (MT) data has been collected along two 400 km profiles in the northern part of the Zagros belt to create the first image of the area's electrical conductivity distribution and to gain insight into how the collision between the two plates is accommodated within the lithosphere and upper asthenosphere. The MT data, measured at 22 long-period sites, was processed using a robust processing technique based on the eigenvalue decomposition method by Egbert (1997) to obtain estimates of the electrical resistivity structure beneath the study area. The phase tensor inversion results indicate the presence of a well-conducting zone at a depth of about 100 km, which may indicate the presence of the asthenosphere. Additionally, the inversion reveals a mid-crustal layer with low resistivity increasing beneath the Arabian plate and probably correlating with the locations of seismic low velocity zones in that region. The result coming from the sites close to the plate's suture shows complications and is probably biased by 3D phenomena. Therefore, the existing 2D studies will be followed by 3D investigations to obtain a meaningful subsurface model of electrical conductivity.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

The geomagnetic field at La Palma (Canary Islands) before, during and after the 2021 eruption at the Cumbre Vieja rift

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After almost 50 years of quiescence, the Cumbre Vieja rift in La Palma underwent a reactivation process that culminated in a volcanic eruption from September 19 to December 13, 2021, preceded by a seismic swarm that started just eight days before the eruption onset. Seismic unrest started in October 2017 and comprised ten seismic swarms in five years, with the last one in August 2021. In July 2021, a magnetic station (CFU) was deployed in Cumbre Vieja, 2 km away from the site where the eruptive vents would open two months later. In September 2021, a second magnetic station (SAN) was installed near the southern end of the Cumbre Vieja rift. Both stations are still in operation today and acquire the total geomagnetic field intensity (F) with a sampling rate of 1 measurement/minute with two Overhauser magnetometers. In this work, we present the results of the analysis of these geomagnetic time series, which led to the identification of several signals of presumed volcanomagnetic origin. Our data revealed a magnetic signal at CFU station with an amplitude of 10 nT and a duration of 10 days by mid-August, one month before the eruption onset. During the eruption, the SAN magnetic station registered a magnetic signal with an amplitude of 17 nT in the second half of October. We analysed possible correlations with other physical parameters and concluded that these signals are the result of changes in the magnetization of rocks beneath the volcanic edifice related with volcanic activity.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Ambient noise tomography of El Hierro island (Canary Islands)

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To better understand the shallow structure of El Hierro island, we determined a 3D S-wave velocity model using Ambient Noise Tomography (ANT). We exploited a dataset recorded by 21 broadband seismic stations deployed at El Hierro island in two surveys realized in 2015 and 2021. This dataset allowed us to obtain empirical Green's functions by cross-correlating seismic ambient noise signals and retrieving 105 dispersion curves using the frequency-time analysis (FTAN). Then we obtained 2-D Rayleigh wave group velocity maps for periods between 0.6 s and 2.6 s through a non-linear multiscale inversion (Cabrera-Pérez et al, 2021). Finally, we performed depth inversion through a Bayesian transdimensional approach to obtain a 3-D S-wave velocity model. The obtained ANT model is merged with a local earthquake tomography model (García-Yeguas et al, 2014). Our study highlights six relevant seismic velocity anomalies. We observed the presence of three high-velocity zones located in the eastern, western and northern parts of the island, which could be related to intrusive bodies possibly associated with the formation of El Hierro island. We also observed three low-velocity anomalies in the northern and southern parts. The anomaly in the North of the island could be related to loose deposits generated by the El Golfo valley megalandslide. The anomalies in the South could be related to porous and highly fractured materials produced during the more recent volcanic episodes.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Linking drone-based photogrammetry with rock mechanical observations of hydrothermally altered rocks of La Fossa, Vulcano Island (Italy)

DOI: 10.57757/IUGG23-2421 - LINK

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Hydrothermal alteration of volcanic rocks is considered a driving factor in volcano instability by altering their strength and permeability. La Fossa of Vulcano Island (Italy), the most southern exposure of the Aeolian volcanic archipelago, is known for its intermittent hydrothermal activity, fumarole locations and volcanic unrest. Here we explore if events such as the 1988 landslide on the northeastern flank, causing a small-scale tsunami, may be facilitated by hydrothermal activity. Due to La Fossa's location, accessibility, altered flanks and periods of escalating fumarole activity, such as the most recent 2021 crisis, La Fossa acts as a great natural laboratory to monitor and observe the effects of hydrothermal alteration. We used remote sensing methods and field-based rock physical property measurements to assess areas that preserve different degrees of hydrothermal alteration. In detail, we (1) acquired close-range photogrammetric data using unmanned aerial surveys and performed a structure-from-motion and classification approach to map alteration areas and (2) performed field-based measurements to provide estimations of rock strength and permeability of the variably altered rocks. Correlating our observations allows us to explore the link between alteration and strength, and therewith between hydrothermal activity and flank instability.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Geomagnetic variations associated with the unrest in 2014 and 2018 at the Kusatsu-Shirane Volcano

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Geomagnetic field measurements at active volcanoes have been performed to investigate the thermal state within the shallow volcanic edifice. At the Kusatsu-Shirane Volcano, repeated and continuous observations around the Yugama crater lake have been conducted by the Kakioka Magnetic Observatory of the Japan Meteorological Agency since the 1970s. The geomagnetic variations up to 2012 obtained from these observations and their causes were reviewed by Takahashi and Fujii (2014). In this study, we introduce the continuous observations of geomagnetic total intensity conducted since 2010 by the Tokyo Institute of Technology and the observed geomagnetic changes. Since observations began, distinct changes probably attributed to the thermal demagnetization of rocks within the volcanic edifice have been identified twice, associated with the unrest in 2014 and 2018. The features of these variations were summarized, and the locations of the magnetic sources were estimated using simple model calculations. The magnetic dipole source that explains the geomagnetic changes observed during the 2014 unrest was estimated to be deep, which is below the pressure source that explains the tilt change during the same period. However, the dipole source for the geomagnetic changes indicating a demagnetizing trend observed in synchronization with the earthquake swarm activity in April 2018 was found to be located beneath the southeastern rim of the Yugama crater lake, which had never previously been estimated. All these sources are located beneath the highly conductive layer inferred near the surface and are thought to be related to the ascent and accumulation of hydrothermal fluids.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Long-term variation in dissolved chemical components contents in Yugama, an active crater lake of Kusatsu-Shirane volcano, Japan, since the 1960s

DOI: 10.57757/IUGG23-3937 - LINK

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Kusatsu-Shirane volcano is a famous active volcano in Japan. The volcano has an active crater lake, Yugama, having subaqueous fumaroles. Yugama is a vital observation object in the chemical monitoring of the volcano. The Yugama water contains polythionate occasionally, and the variation in their concentrations probably connects to the volcano's activity.

During the past half-century, the volcano went through three phreatic eruption activities in 1976, 1982/1983, and 2018. In this study, we constructed precise time-series data for the contents of dissolved components in Yugama since the 1960s. We then discussed the variation in the contents of sulfur species in Yugama and its relation to those of the other dissolved components and the volcanic activity of the volcano.

Even during the unrest period that did not lead to eruptions, changes in the dissolved composition of Yugama were observed. When volcanic activity increases, the dissolved contents of fluoride, chloride, and sulfur oxyanions (sulfate and polythionate) increase. Although the content ratio of chloride to sulfate did not change significantly, those of polythionate to chloride and polythionate to total sulfur species increased significantly. However, the details of the variability vary from active period to active period.

The polythionate content in Yugama water varied synchronized with the ORP value, probably reflecting the SO_2/H_2S ratio in volcanic gasses supplied from subaqueous fumaroles into the lake water. The higher SO_2/H_2S ratio in the gasses might induce the production of polythionate in the shallow hydrothermal system and stabilize them in the lake water.

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Magnetization structure and its temporal change of Miyakejima volcano, Japan, revealed by uncrewed aerial vehicle aeromagnetic survey

DOI: 10.57757/IUGG23-0278 - LINK

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Miyakejima volcano experienced its latest eruption in 2000 with the summit subsidence, and the next event is expected in the near future. An aeromagnetic survey in Miyakejima was conducted in March 2021 in order to investigate the current state of its magnetization structure to identify the potential for another eruption and, thus, mitigate volcanic disaster. The survey flight was conducted using an uncrewed aerial vehicle (UAV), a multirotor drone, to deploy a scalar magnetometer. After processing geomagnetic field data from this survey, in combination with data from previous surveys conducted by using another UAV, an uncrewed helicopter, the average magnetization intensity was determined to be 12.4 A/m. Further, the surrounding area of the crater was relatively highly magnetized; however, the crater rim had a low magnetization intensity. Temporal variation was detected between 2014 and 2021 and dominated the central part of the observation area. Decreased magnetization intensity was identified beneath the caldera, which may become recently demagnetized due to heat supply traveling through fractures in the impermeable layer from the deep heat reservoir.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Insights into Persistent Activity, Crater Formation & Phreatic to Phreatomagmatic Eruptions at Telica Volcano from Multiparameter Observations

DOI: 10.57757/IUGG23-4438 - LINK

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Armando Saballos[3], Wilfried Strauch[3], Virginia Tenorio[3]
[1]Alfred Wegener Institute, Geophysik, Bremerhaven, Germany
[2]Penn State, Department of Geosciences, University Park- PA, USA
[3]Instituto Nicaraguense de Estudios Territoriales, Geofisica, Managua, Nicaragua
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Telica volcano is a persistently restless volcano with activity expressed as long-lived high-temperature fumaroles and magmatic degassing, high rates of background seismicity and frequent phreatic to phreatomagmatic eruptions. Two decades of geophysical, geochemical, and geologic observations indicate: 1) long-lived fumaroles cause hydrothermal alteration and collapse of crater walls, and deposition of debris in the crater; 2) decreases in gas flux, fumarole temperatures, remotely sensed thermal anomalies, and low-frequency seismicity prior to explosions and eruption of hydrothermal minerals and alteration products indicate sealing of the shallow hydrothermal system and conduit; and 3) eruption of a lava dome and ballistic blocks indicate viscous basaltic andesite magma in the conduit. Deposition of crater wall debris may seal the system at a shallow level but does not affect the deeper magmatic – hydrothermal system. Whereas the partial to complete sealing of the volcanic conduit occurs through the deposition of hydrothermal minerals, and the slow migration of viscous magma. These processes move the volcano from an open to a closed system, resulting in phreatic to phreatomagmatic explosions. We developed a numerical model to investigate near-field surface deformation measured by cGPS. Our model incorporates changes in permeability of the conduit due to mineralization, the accumulation of gas beneath the seal, and subsequent increase in pressure of the system driving surface deformation. Increase in pressure leads to failure of the seal and explosions. Improving our knowledge of this transition from an open to closed system is important for forecasting explosive activity at Telica and similar volcanic systems.

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may seal the system at a shallow level but does not affect the deeper magmatic – hydrothermal system. Whereas the partial to complete sealing of the volcanic conduit occurs through the deposition of hydrothermal minerals, and the slow migration of viscous magma. These processes move the volcano from an open to a closed system, resulting in phreatic to phreatomagmatic explosions. We developed a numerical model to investigate near-field surface deformation measured by cGPS. Our model incorporates changes in permeability of the conduit due to mineralization, the accumulation of gas beneath the seal, and subsequent increase in pressure of the system driving surface deformation. Increase in pressure leads to failure of the seal and explosions. Improving our knowledge of this transition from an open to closed system is important for forecasting explosive activity at Telica and similar volcanic systems.

Local Vp/Vs variations during the seismic swarm preceding the 2021 eruption in Fagradalsfjall, Iceland

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Fagradalsfjall is located in the central part of the Reykjanes Peninsula in Iceland. The last eruptions occurred about 7000 years ago, but the Reykjanes Peninsula is seismically active and is episodically hit by large earthquake swarms every 20 to 40 years. This paper, examines the 2021 Fagradalsfjall swarm, which began with a 5.3 magnitude ML earthquake on 24 February and continued for about a month before ending with an eruption on March 19. This swarm was a continuation of the July 2017 (ML < 3.7), December 2019 (ML < 3,7) and July 2020 (ML < 5) in this region, all recorded by 15 stations of the local Reykjanet seismic network. Analyzing the spatiotemporal evolution of the 2021 Fagradalsfjall swarm, we can see that the seismicity originated from the northern part, then moved southward, and finally rebounded to the central part where the eruption occurred. We use the robust double-difference Wadati method to measure in-situ Vp/Vs as a tool to track the presence of magma in different temporal and spatial intervals. The entire dataset consists of 38500 events, which reduces to about 9000 after being relocated by HypoDD and GrowClust and applying some preprocessing constraints to remove outliers such as cross-correlation above 0.85 and phase arrivals at least 8 stations. Furthermore, we limit the Vp/Vs ratio in each event pair between 0.5 and 3 for a better result. Our results are compared with those obtained by application of this method on different earthquake swarms.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

Numerical simulation of hydrothermal circulation within active volcanoes: Constraints from resistivity structure models

DOI: 10.57757/IUGG23-2253 - [LINK]

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Numerical simulation is a useful technique for studying the complex behavior of volcanic hydrothermal systems. Most previous simulations have used highly simplified structures, and few studies have considered the natural heterogeneity of the permeability distribution which significantly affects fluid flow within volcanoes. This is mainly because it is difficult to estimate the subsurface permeability structure. In this study, as a first step towards establishing a comprehensive scheme for constructing a realistic permeability structure, we attempted to numerically reproduce the steady-state hydrothermal system of a volcano using a rough permeability structure based on the three-dimensional resistivity structure. The volcano studied was the Kusatsu-Shirane Volcano (KSV) in central Japan. Several scenarios with different permeability structures were prepared to determine what structures significantly affect hydrothermal flow. In each scenario, saline fluids were injected from the bottom of the domain to simulate hydrothermal circulation within the volcanic edifice. In all scenarios, the fluid that ascended to around the summit area flowed down toward the eastern and western foot of the volcano and discharged mainly along the valleys, reproducing the actual distribution of hot springs around KSV. However, the observed discharge rates were reproduced only when a seal zone surrounding the conduit and low-permeability basement rocks were assumed. Although the constructed permeability structure was relatively simple, the simulation results that considered interpretations of the resistivity model closely reproduced several observed data. This suggests that incorporating information on the resistivity structure can significantly reduce the uncertainty of the hydrothermal fluid flow simulations.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

The evolution of hydrothermal activity and instability of Anak Krakatau 2018-2023, analyzed from satellite and drone data

DOI: 10.57757/IUGG23-2910 - LINK

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In December 2018, the Anak Krakatau volcano was destroyed in a cascade of eruptions following a flank destabilization. A tsunami triggered by these events devastated coastal areas and caused loss of lives, highlighting the importance of better understanding destabilization processes and possible structural weaknesses. Satellite remote sensing data provided by Planet Labs, Pleiades, and TerraSAR-X allow us to monitor volcanic evolution stages at high temporal resolution and to catalog events for the period 2018-2023. We aim to identify possible zones of structural weakness in the newly forming volcanic building, that may pose risks in future development, by focusing on activity patterns like surface degassing and sealing processes. Posteruptive degassing, observed in the crater lake and on the western shore of the island highlights an off-centered activity. Several periods of coverage and reoccurrence of the surficial degassing pattern by tephra and ashes are observed until June 2020, when a lava flow largely covered and effectively sealed the open degassing surface. A second lava flow covers all of the original open degassing surfaces and degassing now exclusively occurs on the eastern margin of the new lava flow. The alternate layering of tephra and lava flows, acting as inclined sealing planes, indicates the possibility of a critical evolution where pressurization and hydrothermal alteration effects of the lateral gas flow might create future zones of structural weakness. We suggest a close monitoring and cataloging of Krakatau's structural evolution, and investigation of the gas-rock interactions to assess their potential to create future sliding planes.

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JS04 - Posters - Monitoring, Imaging and Mapping of Volcanic Areas (IASPEI, IAG, IAVCEI, IAGA)

An aeromagnetic survey using an unmanned aerial vehicle over Azuma Volcano, NE Japan

DOI: 10.57757/IUGG23-2319 - [LINK]

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The volcanic alteration zone at a depth of several hundred meters below the surface is a key feature to assess the degree of the imminence of phreatic eruption; Recent magnetotelluric images indicate that the conductive alteration zone prevents hypocenters of volcanic earthquakes from reaching the surface（Tsukamoto et al., 2018; Tseng et al., 2020; Gresse et al., 2021). A phreatic eruption could occur, when the hypocenters pass through the conducting layer. To approach the surface alteration zone and demagnetized area in the active volcanic edifice, a total intensity aeromagnetic survey using an unmanned aerial vehicle was carried out in 1×2.5 km over Oana Crater, with now on active fumaroles inside, of Mt. Azuma, NE Japan.

The original magnetic anomaly distribution was obtained using Nakatsuka and Okuma (2006) with correcting the main field (IGRF-13) and the diurnal variations. The average magnetization intensity (AMI) was 2.06 A/m estimated by a statistical correlation method (Grauch 1987). After subtracting the contribution of the average magnetization from the original magnetic anomaly, the resultant magnetic anomaly data were inverted into a three-dimensional subsurface magnetization perturbation from AMI using the effective source volume minimization method (Nakatsuka and Okuma, 2014). The result shows a weakly magnetized region below the Tsubakurozawa Crater, where the past eruption occurred in 1893, 1896, juxtaposed with Oana Crater. The weakly magnetized location coincides with the demagnetization source location modeled by using the repeating total magnetic intensity observations (Japan Meteorological Agency, 2020).

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JS05 - Posters - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

RT-HF GNSS mobile network during the 2021-2022 unrest at Vulcano Island

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At the end of the summer 2021, an increase in CO2 emissions at Vulcano brought to an increase in the alert level and, as a consequence, to the upgrade of the monitoring activities by increasing the number of instruments deployed and the rate of the surveys. One of the new devices installed was a geodetic GNSS mobile network for a Real-Time and High-Frequency monitoring of ground deformation, to increase the detail with respect to the existing permanent network. The mobile stations were initially installed at the northern base of the La Fossa crater, where the highest values of soil degassing were recorded. Two stations were co-located with gravimeters, in order to compare and integrate the data. Afterwards, the mobile GNSS array has been re-configured, to investigate the mud pool area. Thus, four stations were installed around the degassing area, one of them being in the same site of the gravimeter. Data has been acquired at 1 Hz rate and are used for the weekly reporting to Civil Protection. It was the first experience of a RT and HF GNSS mobile network in this area and it was the occasion for testing its performance, as well as different approaches for the RTK positioning in order to find the most suitable for the ongoing phenomena. Furthermore, direct data communication and archiving in the institutional database have been implemented for immediate querying from the control room tools. We report the experiences collected during the installation phase, site selection, RTK approaches and ground motion.

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JS05 - Posters - Real-Time GNSS Data and Products Usage: Interoperability and Management Challenges (IASPEI, IAG, IAVCEI, IAPSO)

GNSS-RTT (GNSS - Real Time Tracker), a Software System For Real Time GNSS Data Acquisition, Processing And Visualization.

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During any emergency response, the real-time GNSS data analysis strategies based on differential approach (i.e. Real Time Kinematic) needs some crucial a-priori information on the reference stations.
In addition to their location in an undeformed area, this choice can be also influenced by other parameters (RMS of the time series, battery voltages, transmission on/off, number of visible satellites, etc.). For this reason, we developed an intelligent homemade algorithm BC-RTK (Base Choice - RTK) able to choose the more reliable baselines to potentially provide the best RTK results, it defines stations' priority to the real-time GNSS analysis whose results are stored in a time-series database.
This algorithm is a part of a software, called GNSS-RTT(Global Navigation Satellite System - Real Time Tracker), developed in 2022/2023. It is an open source software that can be either connected to different GNSS receivers through a different type of connection (Tcp/ip, Ntrip, etc.) or linked to a Ntrip Caster. For the solutions, it is able to get the data in different formats (NMEA, LLH,XYZ, etc.) and at different sampling frequencies up to 200 Hz. The data is stored in an optimized database called InfluxDB(https://www.influxdata.com) for real-time and IoT applications. It was developed to manage the data efficiently, allowing both real-time and post-processed visualization. The visualization is performed by means of web applications, such as Grafana (https://grafana.com) or Chronograf (https://www.influxdata.com/time-series-platform/chronograf).

We will describe the technical aspects relating to the presented software and some preliminary results in test cases.

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JS06 - Posters - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

1- D velocity model for the South Western part of Romania. Study case Targu-Jiu area

DOI: 10.57757/IUGG23-3099 - LINK

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The seismicity of the South Western part of Romania is linked to tectonic deformation being the result of the dextral movements at the contact between the Carpathians Orogen and Moesian Platform. The most notable active faults in this region are the Oravita-Moldova Noua Fault and Cerna-Jiu Fault. The crustal structure of this region was investigated through classical and modern techniques such as refraction and reflection profiling, seismic tomography, joint inversion of dispersion curves, and receiver functions. Targu-Jiu region was characterized before 2023 by sporadic small to moderate earthquakes. A well-investigated seismic sequence was produced in 2011-2012. The recent double-shock occurred in the area in February 2023 (5.2 and 5.7 ML) and was followed by more than 700 aftershocks. In order to estimate an improved 1-D velocity model for this active region, we extracted from the Romanian earthquake bulletins 170 events, recorded by Romanian Seismic Network. The events were selected based on the following criteria: a minimum of 20 recorded phases for each individual earthquake, the RMS location of less than 1 second, and a maximum azimuthal gap of 180 degrees. The region's velocity model and station corrections were accurately determined by minimizing the misfit between the model predictions and arrival times. The VELEST algorithm was run on the selected data, using P and S-wave travel times and the initial velocity models for generating new improved velocity models. We noticed a reduction of up to 40% in RMS location errors for all resulting velocity models.

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JS06 - Posters - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Density modeling and elastic parameters calculation in Iran with focus on the Lut Block zone (Eastern Iran)

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[2]*Geomatics Research & Development srl, c/o ComoNExT, Lomazzo, Italy*

We propose a new density model in Iran, with a particular focus on the Lut Block zone, in eastern Iran, through inversion of the gravity field starting from a high-resolution seismic tomography model (Kaviani et al, 2020). The density and seismic velocity model allow us to obtain rheological parameters, as shear modulus, and the physical state, like pressure and pressure gradient. We realize a first density model, using known velocity-density relations for crust and mantle (Brocher et al., 2005; Connolly, 2005) optimized with the gravity data. Then we calculate the final 3D density model from constrained inversion of the gravity field with a Bayesian approach. The density model, together with velocities from tomography, allows to calculate principal elastic parameters, using empirical relations (Telford et al., 1976). The area analyzed is tectonically active and presents numerous right-lateral strike-slip faults, that cause the slipping of the East-Iran and the Lut blocks. We observe a high-density crustal anomaly, beginning in an upper crust zone and increasing in density as it descends to the mantle. This is located in an area in the center of the Lut Block, around which we know a part of the East-Iran Block, the Birjand block, is rotating. We analyze the zone in terms of physical parameters, searching for a relation between the density anomaly and the rotation of the Birjand block around it.

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JS06 - Posters - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Jif3D – an open-source joint inversion platform

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Joint inversion of different geophysical data has been receiving significant attention in recent years due to its potential to improve the quality of subsurface models and provide additional dimensions of analysis over single-data approaches. For example, the relationship between different physical parameters can be used to provide classifications of lithology. However, the technical barrier of entry for new joint inversion methods is very high, as they require efficient forward engines for multiple methods, data and grid management algorithms and useful coupling methods between the different parameters. Jif3D is an open-source C++ joint inversion framework that provides all necessary ingredients for effective inversions in three dimensions. It comprises parallel solvers for gravity, magnetics, DC resistivity, seismic traveltimes, surface waves and magnetotellurics. In addition, a variety of coupling approaches such as Cross-Gradients and Variation of Information are implemented. It can be used as a ready-to-use inversion program or as an experimental platform to develop new approaches thanks to its modular design. Jif3D has been used in a variety of contexts from mineral exploration to large-scale tectonic imaging with different combinations of data. I will show selected case studies using jif3D and discuss possible applications of joint inversion. In particular I will demonstrate the value of joint inversion using seismic, magnetotelluric, gravity and magnetic data from the western United States where currently active tectonics interact with inherited structures to form a complex subsurface.

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JS06 - Posters - Joint Inversion of Different Geophysical Data Sets (IASPEI, IAGA, IAG, IAVCEI)

Exploring Iron Ore deposit around Kiruna with 3-D magnetotellurics

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The efforts of today's society to switch to greener technology and fossil-free energy requires mineral resources. The economical depth of new deposits grows hence deep exploration methods are needed. Magnetotellurics is non-invasive passive electromagnetic method allowing to survey from the surface down to a several tens of km and therefore is a choice when deposit scale information is required. In 2018 a magnetotelluric 3-D array dataset was collected around known magnetite-pegmatite-deposits in Kiruna, Sweden. The survey area is affected by industrial electromagnetic noise from the mine and Kiruna town, which is often a challenge for the magnetotelluric method. Nevertheless, we utilized robust multi-remote reference processing techniques to derive magnetotellurics transfer functions which are in general of a good quality, except a few sites. Many sites exhibit an unusual behavior with phase of main components of the impedance tensor going out of quadrant. This behavior can be indication of noisy data or possibly strong 3D effects. Therefore, we rely on data re-weighting scheme to conclude about the data quality. The final 3-D model was obtained after a few re-weighted least square iterations using diffusion smoothness constrains as model covariance matrix (Second order Tikhonov regularization). Finally, we have obtained a model with stable anomalies at all depths which matches known geology but brings new details and insights into the general understanding of the area.

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JS07 - Posters - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Generation of planetary core zonal flows by orbital forcings or fingering convection

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Zonal flows generation is a long-standing issue in rotating fluids, which can be key in the dynamics of planetary fluid layers (e.g. planetary cores). They are indeed believed to play a significant role in angular momentum exchanges between liquid layers and surrounding solid domains (e.g. Roberts & Aurnou, 2012). Moreover, mean flows could be unstable (e.g. Sauret et al., 2014; Favier et al., 2014), which could sustain space-filling turbulence and mixing. Therefore, understanding the formation of mean flows is essential to model the fluid dynamics of many rapidly rotating systems.

Zonal flows of planetary liquid cores are usually studied as originating from convection in rotating spheres. In the frame of the ERC THEIA (grant agreement no. 847433), we consider here two alternative origins. First, zonal flows can be generated by orbital forcings (e.g. tides, precession) via nonlinear effects within the Ekman layer (Cébron et al., 2021). These flows survive in the relevant regime of vanishing forcings and viscosity. Their competition with bulk driven zonal flows are then considered for various planets and moons. Second, zonal flows can emerge from double-diffusive convection (DDC) in stratified cores (Monville et al., 2019). Applying our results to the early Earth, we obtain that double diffusion can reduce the critical Rayleigh number by four decades, suggesting that its core was prone to turbulent DDC, with large-scale zonal flows.

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JS07 - Posters - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Effect of heat flux heterogeneities at the core-mantle boundary on geodynamo simulations

DOI: 10.57757/IUGG23-1565 - [LINK]

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The heat flux at the core-mantle boundary (CMB) is a key parameter for core convection and the geodynamo. Both the mean value and the lateral variations of the CMB heat flux affect the behavior of the geodynamo, and notably the stability and strength of the magnetic dipole in numerical simulations. Inside the Earth, the CMB heat flux is controlled by mantle convection, with possibly large lateral variations. Thus, this could be a significant parameter influencing the dynamo.

This work aims at acquiring a more complete understanding of how lateral heterogeneities of CMB heat flux affect the geodynamo while other relevant parameters are pushed to more realistic values. For this purpose we ran geodynamo simulations with degree 1 and 2 spherical harmonic patterns of heat flux at the CMB. We especially focus on the heat flux distribution between the poles and the equator.

Most of the explored patterns tend to decrease or have little effect on both the magnetic energy and the dipolar fraction of the magnetic field. However, we find that adjusting the distribution between polar and equatorial cooling of the core noticeably affects the dynamo. An equatorial cooling weakens the magnetic dipole, while a moderate polar cooling strengthens the magnetic dipole. These effects are especially strong for moderate heterogeneity amplitudes. Cooling the equator or the poles tend to promote convection outside and inside the tangent cylinder, respectively. The effect on reversal rate is also explored, and exhibits a complex behaviour.

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JS07 - Posters - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Experimental and numerical investigations of the topographic core-mantle interactions

DOI: 10.57757/IUGG23-2907 - LINK

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[3]ISTerre, Geodynamo group, Grenoble, France

Enclosed fluid layers in planets and moons are ubiquitous and play an important role in the heat and angular momentum balance as well as mixing and energy dissipation. For those rapidly rotating fluid layers, most steering mechanisms such as convection , tides, precession/nutations, librations have been studied mostly in smooth spheres, spheroids and in some cases ellipsoids, neglecting a possible roughness or small scale topography at the boundaries. Meanwhile such anomalies have been considered in stratified oceans and atmospheres showing they contribute significantly to the heat transport, angular momentum exchange and energy dissipation. In the present study we employ experimental and numerical techniques to investigate these questions in the case of neutrally buoyant rapidly rotating fluids. Considering a rotating cylindrical fluid volume with an immersed disc with a single wave length topography pattern oscillating along the rotation axis, we measure the torque necessary to drive the oscillation and characterise the flow structure to identify the fundamental mechanisms at play. In this presentation we report the preliminary results at a fixed Ekman number (E~1e-5) and topography pattern as a function of the oscillation frequency and amplitude.

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JS07 - Posters - Geophysical Constraints on the Earth’s Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Plesio-geostrophy for Earth's outer core: Recent advances

DOI: 10.57757/IUGG23-1122 - LINK

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The main tools by which we can study the dynamics of Earth’s fluid core are direct numerical simulations (DNS). In spite of their success, their high computational cost prevents DNS from reaching Earth-like parameters regimes.

Previous studies support the idea that the vast majority of the kinetic energy in the core is contained in columnar, vertically invariant structures. Columnar flow models capitalise on this observation and transform the original, 3D governing equations in a simplified, 2D set. These models have proven their potential in simulating the dynamics of Earth’s fluid core in extreme parameter regimes. However, current approaches are not capable of treating the magnetic field within the same 2D framework.

Plesio-geostrophy (PG) was developed to overcome this limitation. Our PG model describes fluid flows, magnetic field and temperature via 2D variables. We tested our novel PG methodology on a set of linear problems of relevance to the dynamics of Earth’s fluid core: inertial and magneto-hydrodynamics waves propagation, and onset of thermal convection. All diffusivities are taken into account. The effect of viscous boundary layers is parameterised via a novel, fully spectral numerical methodology that does not require special treatments of the critical latitudes. We successfully benchmarked the PG model results against both 3D and other columnar flow models and calculated solutions at geophysically relevant parameter regimes.

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JS07 - Posters - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Free Core Nutation, Tilt-Over mode, and other inertial modes of the Earth: Clarification

DOI: 10.57757/IUGG23-0956 - LINK

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The Earth's rotation varies in time under the gravitational influence of nearby objects, mainly the Sun and the Moon. The response of the Earth to these gravitational disturbances depends on its internal structure. In particular, the existence of the free oscillatory motion of the liquid core called the Free Core Nutation (FCN) amplifies the planet's nutation in the diurnal retrograde frequency bands (as measured in the terrestrial frame of reference). This mode is related to another mode known to fluid dynamicists as the Spin-Over mode (SOM), the latter being one an infinite set of inertial modes restored by the Coriolis force in rotating fluid bodies. In this work, we review the relation between the FCN and SOM and show how the frequency of the latter can influence the FCN frequency in a non-trivial way when the two are close to each other. We also clarify the relation between these modes and another one known as the Tilt-Over Mode (TOM) sometimes conflated with the SOM in the literature. We also explore how other inertial modes may affect the Earth's rotation and magnetic field.

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JS07 - Posters - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

Turbulence in the boundary layer of precession-driven flow

DOI: 10.57757/IUGG23-4286 - LINK

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The boundary layer (in the outer core) between the core and the mantle is known to be thin, with the nominal value about 0.11 meters. The presence of turbulence in the boundary layer has been proposed as a mechanism to explain the observed damping of the Free Core Nutation (FCN). However, the small amplitude of FCN makes the turbulence scenario unlikely. A recent study shows that the precession-driven flow is at the margin of turbulence. Here, we use a local Cartesian box model to study numerically the boundary layer. Our numerical results show that the boundary layer at certain latitudes is not turbulent. By considering the total dissipation in the boundary layer, we find an increase by a factor of 1.86 compared to the laminar solution, implying that the effective viscosity is increased by a factor of 3.5. This may have implications for the chemical interaction occurring at the core-mantle boundary.

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JS07 - Posters - Geophysical Constraints on the Earth's Deep Interior Combining Modelling and Observations (IASPEI, IAGA, IAG, SEDI)

The influence of a heterogeneously conducting mantle on the secular variation of the magnetic field

DOI: 10.57757/IUGG23-4454 - LINK

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Convection in the liquid outer core generates the Earth's magnetic field. Observations suggest that the secular variation of the magnetic field is weaker under the Pacific region. In turn, this indicates that flow in this region at the surface of the core is weaker. One hypothesis to explain this is that the conductance of lower mantle is higher in this region or, alternatively, that it features stratified core fluid trapped under topographic undulations. This leads to a larger electromagnetic coupling, attenuating the flow. In this work, we will test this hypothesis using numerical simulations of the geodynamo, in which we impose heterogeneous mantle conductance.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

The thickness of the thermal lithosphere in China and its geodynamic significance

DOI: 10.57757/IUGG23-1314 - LINK

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Based on the latest heat flow data of mainland China and the fine crustal structure data, we calculate the thickness of thermal lithosphere for each heat flow measurement point by solving one - dimensional steady heat conduction equation. The results show that the thickness of thermal lithosphere varies greatly in different areas. By comparing the thickness between thermal lithosphere and seismic lithosphere of the three cratons in China, we concluded that: 1) The western part of the Tarim craton, the middle - upper Yangtze craton, the western part of the NCC and the southern part of the NCC still remain stable, while the eastern part of NCC, the lower Yangtze craton and the southeastern part of the Tarim craton were thinned significantly; 2) In the western NCC, the thickness of thermal lithosphere, seismic lithosphere, and rheological boundary layer(RBL) all thin from west to Yinchuan - Hetao depression in northeast and Fenwei depression in southeast; 3) In the east NCC, the thermal lithospheric thickness of Bohai Bay Basin and the southern part of NCC differs significantly. The thickness of thermal lithosphere in the southern part of NCC is about 60 km thicker than that in Fenwei depression, even though Fenwei depression is to the west of it and theoretically less influenced by subduction of the Pacific plate. 4) The thickness of thermal lithosphere, seismic lithosphere, and RBL of the Yangtze craton gradually decrease from west to east, which may be controlled by the subduction of the Pacific plate.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Thermal conductivity variations of upper crustal rocks at elevated temperatures (25-300 oC) and their implication in 1-D crustal thermal modeling

DOI: 10.57757/IUGG23-1090 - LINK

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Knowledge of the downward variation of thermal conductivity within Earth's interior is an essential parameter for accurately estimating the sub-surface temperature distribution. The variation is dominantly controlled by temperature and, to a very less extent, by pressure. The temperature dependence is distinct for various rocks and higher for upper crustal rocks than the lower crustal rocks, implying the utmost necessity of detailed study for upper crustal rocks. In thermal modeling, two temperature coefficients are commonly considered for the upper and lower crust. But the upper crust generally consists of a wide variety of rocks.
In the present study, thermal conductivity variation with temperature has been studied in the laboratory by a steady-state method in the temperature range of 25-300 °C on different types of upper crustal rocks, e.g., granitoids and rhyolites. Results show that the temperature dependence of thermal conductivity for different varieties of granitoids, i.e., alkali feldspar granite to monzogranite and granodiorite to tonalite to quartz diorite, indicate two distinct ranges and rhyolites lie between these two varieties. The study also depicts that a single temperature coefficient for the upper crustal rocks needs to be modified, and appropriate values should be considered, depending upon the variations in rock formation of the upper crust. The observed wide variations in the temperature dependence of thermal conductivity for different varieties of upper crustal rocks will be useful for precise sub-surface thermal modeling. The study also investigated how the difference in temperature coefficient for the upper crust can produce a difference in thermal structure.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow variations in five new boreholes in the Vogtland geodynamic region

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This work details the variations in heat flow density and thermal properties of rocks in five 300–450 m deep fully cored boreholes in the seismically active part of the West Bohemia at the border of Czechia and Germany. All the boreholes were drilled in the crystalline units, with boreholes S1 (Landwüst, 50.26°N, 12.33°E), S2 (Tisová, 50.35 °N, 12.50 °E) and S3 (Studenec, 50.26 °N, 12.52) intersecting metamorphic rocks, borehole S4 (Bažina, 50.15°N, 12.21°E) passing through the sedimentary cover of a newly discovered maar and the underlying granite, and borehole PTP-3 (Potůčky, 50.43 °N, 12.78 °E) completely drilled in granite. Precise repeated temperature logging was performed for all the boreholes, and due to the hilly terrain, topographic corrections were applied using 3-D numerical models to account for the effects of topography on the borehole temperatures. Thermal properties, including their anisotropy, were determined in the laboratory on ten or more rock samples from each borehole. Hence, it was possible to analyze depth variations of the heat flow in the individual boreholes. The largest variations occur in the boreholes located in metamorphic rocks. Due to rock heterogeneity, anisotropy of thermal properties, effect of climate change and water movement, the heat flow density ranges from less than 50 mW m^{-2} to more than 100 mW m^{-2}.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Heat flow and thermal structure of the marginal seas in the Western Pacific Region

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Marginal seas develop in the western Pacific region, with various evolutionary stages and geological characteristics. Geothermal field could provide some clues for understanding regional tectonics, thus revisiting the geothermal regime of the marginal seas in western Pacific region is in demand and available with the increasing heat flow data. Combing the updated global heat flow dataset of IHFC and other observations, heat flow and thermal structure of the marginal sea basins are analyzed. Our results demonstrate that heat flow varies much among the marginal seas, and the average values for the Okhotsk Sea, Japan Sea, Okinawa Trough and South China Sea are 80 mW/m^2, 93 mW/m^2, 210 mW/m^2 and 75 mW/m^2, respectively, indicating different ages. While the subduction zones exhibit similar geothermal patterns, with relatively low heat flow in the fore-arc regions, extremely high but variable heat flow in the volcanic arcs, and generally high heat flow in the back-arc regions. High heat flow anomalies are observed within the marginal seas, as a result of fluid circulation and recent volcanic activities. High temperature and large heat flow in the back-arc regions can be attributed to the heat contributions from the mantle. The heat flow verse age relation for marginal sea basins can be roughly expressed by $Q(t)=585.8\ t^{-1/2}$. It seems that this *Q-t* relation for marginal seas does not significantly differ from that for oceanic basins. Given the uneven coverage in heat flow data and vagueness in crustal age, this expression needs to be determined with caution in further study.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

The quality assessment of the German heat flow database

DOI: 10.57757/IUGG23-3270 - LINK

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The Global Heat Flow Database of the International Heat Flow Commission (IHFC) is currently under fundamental revision. Here, we present a critical assessment of the terrestrial heat-flow-density data for Germany. The collected legacy data from Germany cover entries from 596 heat-flow locations over a time span of more than 60 years, showing differences in documentation and the availability of metadata. To assess the data, we follow a multi-step procedure: first, we screened the original literature, updated the heat flow data and revised them for completeness and reproducibility. Database entries with missing data essential for heat flow determination (like temperature gradient, thermal conductivity) are flagged as not reliable as they cannot be scientifically reproduced nor quality assessed. This strict procedure is necessary for setting up a dataset following scientific criteria and results in a reduction of the original data set by almost 80% to 138 locations. These were assessed in terms of methodological quality and labeled for different overruling effects, like paleoclimate, heat refraction, or fluid movements. The (area-weighted) average terrestrial heat flow for Germany is 78 ± 7 mWm^{-2} which is by almost 20% higher compared to earlier estimates (ca. 65 mWm^{-2}). The regional average heat flow across Germany varies by the order of 40 %. However, considering a radius of 10 km around each location, the heat flow remains uncertain for ca. 90% of the German onshore area, which raises the demand for new systematic heat-flow measurements in Germany.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Marine geothermal heat flow research at the MARUM – Center for Environmental Sciences, University of Bremen

DOI: 10.57757/IUGG23-0694 - LINK

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[2]*University of Bremen, Geoscience- Geophysics, Bremen, Germany*

Marine heat flow data provide fundamental insights into thermal processes and advective heat transport occurring near and below the seafloor. Processes that influence and are influenced by heat transport within seafloor sediments and basement rocks include:

- the thermal evolution of the oceanic crust and lithosphere;
- the geodynamics of plate boundaries and mantle convection;
- fluid circulation and associated impacts on water-rock interactions, seismicity, tectonics, and magmatism;
- occurrence and stability of gas hydrates;
- maturation of hydrocarbons at passive margins.

Understanding these processes involves the quantification of energy and fluid fluxes, requiring knowledge of the thermal state deduced from observations that include heat flux, sub-bottom temperature, and thermo-physical sediment properties.

Our main objective is the presentation of methods, instrumentation, and recent and on-going projects to demonstrate the wide-range field of application. The Faculty of Geosciences and MARUM (University of Bremen) have a longstanding record of high-quality research in the field of marine heat flow studies. We present exemplary case studies from our field of expertise relating to subduction zones (seismogenic zones), gas hydrates, hydrothermal processes (Layer 2A, fault zones, fracture zones), and ridge related processes. Further on, economical projects like assessment and monitoring of thermal impact of buried off-shore power cables from wind farms on the environment come into focus.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Initial Results of Heat Flow Acquisition from a Gas Hydrate System on the Amazon Deep Sea Fan

DOI: 10.57757/IUGG23-3014 - [LINK]

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[1]Sorbonne Université, Institut of Earth Sciences ISTeP, Paris, France
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The Amazon deep sea fan is a dynamic setting in which widespread seafloor fluid vents record degassing of a gas hydrate system hosted within an upper slope thrust-fold belt linked to gravitational collapse of the depocentre. This system is to be investigated during the AMARYLLIS-AMAGAS campaign of the R/V Marion Dufresne, to take place in May-June 2023 as a collaboration between research groups in Europe and Brazil. One aim of the campaign is to study the spatial distribution and stability conditions of the shallow gas hydrate reservoir in relation to temperature changes in the past, fluid migration and venting, and to the triggering of the giant slope failures that have recurrently extended across the fan. Three heat flow transects within a 200 km^2 area of the upper fan will target seismically-observed BSR (bottom simulating reflection) patches associated with fluid venting structures at the crests of thrust-fold anticlines. Temperature gradients will be measured using autonomous high-precision temperature probes attached to core barrels, while thermal conductivity will be measured onboard using a needle probe instrument on recovered sediment cores. Together with hydroacoustic and geochemical datasets to be acquired during the campaign, the results are expected to yield insights into the dynamics of the gas hydrate system in relation to subsurface fluid flow and changes in the heat flow in sediments, as well as new information on the poorly-constrained background regional heat flow regime of the Amazon deep-sea fan.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Thermophysical properties for the major rock formations of the Western Himalaya: Implications for 2-D conductive thermal modeling

DOI: 10.57757/IUGG23-1095 - LINK

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Thermal modeling of the lithosphere is essential to understand the geodynamics, seismogenesis, and crustal evolution of any region. Surface heat flow, radiogenic heat production, and thermal conductivity variations with temperature are the primary parameters that influence thermal modeling. The Western Himalaya is devoid of all these parameters, which hindered accurate thermal modeling of the region. In the present study, we have measured the above thermophysical properties in the laboratory for the major rock formations of the Western Himalaya along three NW-SE profiles. The major rock formations include sandstone, limestone, dolomitic limestone, slate, phyllite, quartzite, schist, gneiss, and granitoid. Thermal conductivity and heat production of these rocks vary from 2.6 to 5.4 $Wm^{-1}K^{-1}$ and 1.7 to 2.6 μWm^{-3}. The crustal structure along one of the profiles, i.e., Tanakpur-Pangla profile (150 km length), is made using available geological and geophysical (seismological and gravity) information, along with new data on rock thermal conductivity and its variation with temperature and radiogenic heat production to obtain 2D conductive thermal structure beneath the region by finite element method. The 2D temperature-depth distribution along this profile covering Siwalik, Lesser Himalaya, and Higher Himalaya formations reveals that the temperature at Moho varies from 450 °C to 750 °C. At a few locations, subsurface temperatures estimated from the 1D conductivity models are in good agreement with that of the 2D results within the uncertainty limits. The results of 2D thermal modeling provide significant progress in understanding of the first-order characteristics of the conductive thermal field in the Western Himalaya.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

A review of heat-flow data from the seas surrounding the Italian peninsula

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Several heat-flow data from the seas of the Italian peninsula, originally scattered in several publications, are gathered in the Global Heat Flow Database (GHFD) Release 2023 (https://doi.org/10.5880/fidgeo.2021.014) and national files. Although data are accessible, it is intrinsically difficult to discern whether they are affected by deviations from purely conductive, steady-state heat transfer unless the original papers are carefully inspected. The superposition of different biases can contaminate the heat-flow values. Uncritically contouring can thus lead to misleading thermal patterns. Moreover, the uneven spatial distribution of heat-flow sites and the differences in measurement techniques may cause additional difficulties in the interpretations. Depending on the possible targets (e.g., calculation of crustal geotherms, modelling or characterisation of advective systems, evaluation of geothermal energy potential), *ad hoc* filtering should be applied to remove the different effects. Within the Global Heat Flow Data Assessment Project (2021-2025) framework, initiated by the International Heat Flow Commission (http://www.ihfc-iugg.org), we reviewed heat-flow data collected during several surveys since the 1960s. We checked the original publications to identify misplaced or forgotten data in the GHFD. The review was based on the newly adopted standard for reporting and storing heat-flow data. Data were critically reviewed, validated and corrected for terrain effects. New heat-flow data from deep wells were also inferred through a minimisation technique accounting for temperatures, radiogenic heat production and the thermal conductivity variation with depth. We obtained significant heat-flow estimates characterising the size and intensity of shallow and deep tectonic events that left a thermal signature in the seas surrounding the peninsula.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

A method for determination target areas of hot dry rock resources: A case study in continental China

DOI: 10.57757/IUGG23-1483 - LINK

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Geothermal resources have been recognized as an important part of clean renewable energy. The exploration, development, and utilization of geothermal resources, especially the Hot Dry Rock (HDR) resources, are of great significance for achieving carbon peaking and carbon neutrality. However, there is no comprehensive evaluation method to determine the HDR target areas, and the evaluation scale and application disciplines are relatively simple. In this paper, we studied the optimization of the distribution target area of HDR resources through multi-scale and multidisciplinary method, and formed a set of generalized and demonstrative process to guide the exploration of HDR resources. Besides, the Expert scoring method was used to improve the target selection from a qualitative study to a quantitative semi-quantitative study, making the decision more specific and more reliable.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Thermal effect of Emeishan basalt on Paleo-heat flow of the Sichuan Basin: numerical modeling

DOI: 10.57757/IUGG23-1677 - LINK

Jinhui Wu[1,2], Lijuan He[1], Liwen Yan[1,2], Chaoqiang Chen[1,2]
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[2]University of Chinese Academy of Sciences, College of Earth and Planetary Sciences, Beijing, China

The Sichuan Basin is an important hydrocarbon-bearing basin in China, and its southwestern part is located in the outer zone of the Emeishan Large Igneous Province. The thermal influence of Emeishan basalt on hydrocarbon development in the Sichuan Basin has been of great interest. Recent paleo-heat flow recovery calculations have yielded the presence of high paleo-heat flows greater than 100 mW/m2 duirng the Permian at some points in the basin, which are thought to be related to Emeishan basalt. In order to understand the causes of these high paleo-heat flows and the thermal effects of basaltic magma overflowing to the surface on the lower strata, the thermal effects of Emeishan basalt were simulated by 2D finite element method. The following conclusions are drawn: (1) The changes in surface heat flow generated by the intrusion of Emeishan basaltic magma into the bottom of the lithosphere and the bottom of the crust are both inconsistent with the high paleo-heat flow of >100 mW/m2 during the Permian of the Sichuan Basin, and magma intruded into the interior of the crust can cause such high paleo-heat flows.(2) The thermal disturbance caused by different thicknesses of magma at the surface to the lower strata at different depths was calculated. The thicker the magma at the surface and the shallower the overlying strata, the greater the thermal disturbance of the magma to the strata, while the adjacent strata are unaffected. The thermal influence on the hydrocarbon source rocks can thus be inferred.

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JS08 - Posters - Advances in Heat Flow Studies: From Fundamental Geodynamic Understanding to Geothermal Energy Applications (IASPEI, IAVCEI (IHFC))

Thermal lithospheric thickness and bottom boundary morphology of the North China Craton after thermal subsidence

DOI: 10.57757/IUGG23-1336 - LINK

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The present day's thermal lithospheric thickness is usually calculated by one or two-dimensional steady-state heat conduction equation. Using the latest measured heat flow data of the North China Craton(NCC) and the one-dimensional steady-state heat conduction equation, the calculated thermal lithospheric thickness of the NCC is between 34.8-190 km. There are some regions, whose lithosphere is very thin, and the lithosphere adjacent to them is very thick, so the bottom boundary of the lithosphere fluctuates greatly. The last thinning of the NCC stopped at~24 Ma and then entered the thermal subsidence period. To study whether the fluctuates of the bottom boundary of the lithosphere can be maintained during the long-term thermal subsidence process, a thermal subsidence model was established. The modeling results show that after the thermal subsidence of 24 Ma, the fluctuates of the bottom boundary of the lithosphere are difficult to maintain, and the present day's thermal lithospheric thickness of the NCC should not exceed 73 km, and the maximum surface heat flow value of the NCC is 75.6 mW·m^{-2} due to the deep thermal state. The high heat flows anomaly in the NCC is more caused by shallow activities and cannot reflect the deep thermal state. After correction, the current thermal lithospheric thickness of the North China craton is ~73-190 km, and the bottom boundary of the lithosphere changes gently.

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JS09 - Posters - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Building resilience in coastal communities: A comprehensive approach to making Malta Tsunami-Ready

DOI: 10.57757/IUGG23-1797 - LINK

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[2]UNESCO, Intergovernmental Oceanographic Commission, Paris, France

With the highest population density per square kilometre in Europe, and an intensive coastal land use, the Maltese islands recognize the importance of becoming a Tsunami-Ready(TR) country. Through the UNESCO-IOC-led project CoastWAVE, funded by DG ECHO, the UNESCO-IOC Tsunami-Ready Recognized status is first being implemented on a smaller scale in the town of Marsaxlokk, on the southeast coast of Malta. In order to evaluate the population's sea level related coastal hazard understanding and awareness, a risk perception questionnaire about tsunami, sea-level rise and storm surge was carried out, involving different target groups representing the local population. The population showed a general misconception mainly regarding the tsunami and storm surge terms because they are familiar with the impact of the latter in Marsaxlokk. The younger population showed insufficient understanding of the natural signs (e.g., sea drawback) of a tsunami, the risk and potential impact in the locality. Further outreach activities will be carried out in Marsaxlokk, informed by the key survey findings. To fulfil one of the twelve TR Indicators (approved inundation maps), a series of tsunami propagation scenarios were also carried out through the numerical model HySEA to explore propagation times, inundation area and run-up at Marsaxlokk and the Grand Harbour (Valletta). The simulated scenarios included a magnitude 7.1 earthquake-generated tsunami based on the 1908 Messina Strait tsunami, which produced well-documented high sea level records around Malta. The results of the CoastWAVE project will contribute towards the future elaboration of a national tsunami awareness, preparedness and early warning programme.

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JS09 - Posters - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Seismic monitoring of Geohazards in Uzbekistan

DOI: 10.57757/IUGG23-0119 - LINK

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The aim of research is to develop a seismic monitoring technique in the Uzbekistan to improve the efficiency of landslides, mudflows hazard prediction.

Based on the obtained scientific results: (1) developed seismic monitoring system to improve the reliability and quality of landslides, mudflows forecasts; (2) created catalog of seismograms is designed to identify seismograms of explosions in a quarry, remote and nearby earthquakes, landslides and mudflows movements; (3) based on the analysis of refracted wave data on Angren brown coal open pit, liquefied layers with the danger of sudden landslides movement were identified; (4) a computer program has been developed using mathematical modeling to more accurately identify the initial part of the longitudinal (P) and transverse (S) seismic waves.

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JS09 - Posters - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

Improving REGARD: real-time finite fault estimates with dense GNSS CORS network GEONET in Japan

DOI: 10.57757/IUGG23-2198 - LINK

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GNSS CORS Division- Geodetic Observation Center, Tsukuba, Japan

GNSS continuous observation enables us to rapidly estimate a finite fault model for a large earthquake without saturation of magnitude. Geospatial Information Authority of Japan (GSI) operates a dense and nationwide GNSS continuous observation network named GEONET, which is capable of providing 1Hz displacement data in real-time. After a gigantic 2011 earthquake in Japan, GSI in collaboration with Tohoku university launched a REGARD (REal-time GEONET Analysis system for Rapid Deformation monitoring), which offers a finite fault model based on the real-time displacement data observed in GEONET. The REGARD system has successfully provided the co-seismic displacement and finite fault model information for recent M~7 or larger earthquakes. These results are provided to government agencies in a few minutes from an earthquake occurrence and are taken advantage of their initial response and tsunami prediction.

To achieve the highest reliability in REGARD, we seek the possibility of applying precise point positioning (PPP) instead of the current relative positioning. PPP can improve the robustness of the real-time positioning subsystem in REGARD by its nature of single positioning. The precise satellite orbit and clock information is generated using MADOCA developed by Japan Aerospace Exploration Agency (JAXA). The satellite orbit and clock includes not only GPS and GLONASS but also QZSS, the Japanese satellite positioning system. In our performance assessment, PPP showed a cm-level accuracy, which is close to the performance of RTK.

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JS09 - Posters - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)

A risk-driven approach in assessing the potential effectiveness of earthquake early warning for schools in the Patras region, Greece

DOI: 10.57757/IUGG23-3441 - LINK

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[2]European Centre for Training and Research in Earthquake Engineering EUCENTRE, Dept of Risk Scenarios, Pavia, Italy
[3]National Observatory of Athens, Institute of Geodynamics, Athens, Greece

Earthquake early warning (EEW) constitute a major tool for seismic resilience enhancement in modern societies, helping mitigate some of the devastating effects of earthquakes (e.g., deaths, business interruption) in the face of increasing exposure and vulnerability to seismic events worldwide. However, traditional EEW approaches (such as feasibility studies and decision-making related to triggering alerts by different end users) are essentially based on seismological considerations.
In this study, jointly developed with the University College London in the framework of the EU H2020 TURNkey Project (https://earthquake-turnkey.eu/), we adopt a risk-based approach to EEW. We present the results of a state-of-the-art feasibility study for EEW in schools performed across the Patras region of Greece, which combines traditional seismologically-driven EEW decision criteria (warning time) with proxy risk-oriented measures for earthquake impact (building fragility and the number of exposed students). The results, showing the effectiveness of EEW under certain conditions, are the premises for the demonstration of an innovative end-user-centred approach for improved risk-informed decision-making on triggering EEW alerts, which merges earthquake-engineering-related seismic performance assessment procedures and metrics with multi-criteria decision-making within an end-to-end probabilistic framework. The approach, demonstrated using an archetype school building for the case-study region, emphasizes that the best action (i.e., “trigger” or “don’t trigger” an EEW alert) for a given level of ground shaking depends on the stakeholder preferences towards the predicted damage/loss estimates consequences.

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JV03 - Posters - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

Comparison of the arrival times of the Hunga Tonga – Hunga Ha'apai Lamb wave with the 1883 Krakatoa observations

DOI: 10.57757/IUGG23-3907 - [LINK]

Ronan Le Bras[1], *Paulina Bittner*[2], *Gerard Rambolamanana*[2], *Pierrick Mialle*[2], *Jolanta Kusmierczyk-Michulec*[2]
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[2]*CTBTO, International Data Centre, Wien, Austria*

The Hunga Tonga - Hunga Ha'apai (HTHH) eruption of 15 January 2022 was an exceptional event by the period, magnitude, and duration of propagation of the atmospheric waves it generated, circling the globe multiple times. Even though several volcanic eruptions in the past 150 years era of scientific instrumentation generated notable barometric disturbances, the HTHH eruption is comparable only to the Krakatoa eruption of 1883 by the magnitude of the atmospheric pressure waves that it generated. For instance, the very energetic Mt Pinatubo eruption of 1991 did not produce pressure waves of the same period and magnitude as the Krakatoa or HTHH eruptions. An analysis of the timing of the multiple passes at barometric stations is reported in Symons (1888) for the Krakatoa. Since the HTHH event also gave rise to a pressure wave that circled the Earth's atmosphere multiple times in the last 134 years, it is of interest to perform similar timing statistics on the multiple passages at stations that recorded them. A review of the Krakatoa analysis and a comparison with the HTHH are presented, with possible implications for the changes in the global state of the atmosphere during the interval between the two events.

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JV03 - Posters - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

Geomagnetic detection of the atmospheric acoustic resonance at 3.8 mHz during the Hunga Tonga eruption

DOI: 10.57757/IUGG23-3864 - [LINK]

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Modeling studies have predicted that the acoustic resonance of the atmosphere during geophysical events such as earthquakes and volcanos can lead to an oscillation of the geomagnetic field with a frequency of about 4 mHz. However, observational evidence is still limited due to scarcity of suitable events. On 15 January 2022, the submarine volcano Hunga Tonga-Hunga Ha'apai (20.5°S, 175.4°W, Tonga) erupted in the Pacific Ocean and caused severe atmospheric disturbance, providing an opportunity to investigate geomagnetic effects associated with acoustic resonance. Following the eruption, geomagnetic oscillation is observed at Apia, approximately 835 km from Hunga Tonga, mainly in the Pc 5 band (150–600 s, or 1.7–6.7 mHz) lasting for about 2 hr. The dominant frequency of the oscillation is 3.8 mHz, which is consistent with the frequency of the atmospheric oscillation due to acoustic resonance. The oscillation is most prominent in the eastward (Y) component, with an amplitude of about 3 nT, which is much larger than those previously reported for other events (<1 nT). Comparably large oscillation is not found at other stations located further away (>2700 km). However, geomagnetic oscillation with a much smaller amplitude (∼0.3 nT) is observed at Honolulu, which is located near the magnetic conjugate point of Hunga Tonga, in a similar wave form as at Apia, indicating interhemispheric coupling. This is the first time that geomagnetic oscillations due to the atmospheric acoustic resonance are simultaneously detected at magnetic conjugate points.

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JV03 - Posters - Hunga Tonga (IAVCEI, IAMAS, IAPSO, IASPEI, IAGA, IAG)

The eruption of the Hunga Tonga-Hunga Ha'apai volcano on 15 January 2022 as observed at seismic stations in Germany

DOI: 10.57757/IUGG23-0335 - LINK

Thomas Plenefisch[1], Andreas Steinberg[1], Stefanie Donner[1], Peter Gaebler[1], Patrick Hupe[1], Christoph Pilger[1], Ole Roß[1], Lars Ceranna[1]
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B4.3 Federal Seismological Service- Nuclear-Test Ban, Hannover, Germany

On 15 January 2022 at 04:15 UTC, an enormous explosive eruption of the Hunga Tonga-Hunga Ha‘apai submarine volcano (short: Hunga) occurred in the Tonga-Kermadec volcanic area. Strong Lamb and tsunami waves were generated. Besides these phenomena also seismic waves could be observed on seismic stations all over the world.

Consequently, seismic body and surface waves of the Hunga main explosion were recorded at seismic stations in Germany. The onset times of PKPbc phases determined at stations of the German Regional Seismic Network (GRSN) as well as corresponding slowness and azimuth calculated by array methods allowed an unambiguous assignment to the Hunga event and an epicenter localization deviating approximately 1 to 1.5 degrees from the volcano. Furthermore, at least one additional event is detected about 4 minutes after the main event.

To assign a seismic magnitude to the Hunga event, we analyzed the surface wave trains. The Ms magnitudes vary between 5.8 and 6.3 within the individual stations of the GRSN, with a mean value of 6.0.

The Tonga-Kermadec subduction zone is characterized by strong earthquake activity. This allows us to compare seismic recordings of the Hunga event with those of earthquakes from the same area with shallow focal depths and comparable magnitudes. It turns out that PKP phases of the Hunga eruption have significantly smaller amplitudes in the short-period range than for the compared earthquakes but similarly strong in the long-period range. We conclude that a long-period excitation is characteristic for the seismically relevant focal process of the Hunga event.

On 15 January 2022 at 04:15 UTC, an enormous explosive eruption of the Hunga Tonga-Hunga Ha‘apai submarine volcano (short: Hunga) occurred in the Tonga-Kermadec volcanic area. Strong Lamb and tsunami waves were generated. Besides these phenomena also seismic waves could be observed on seismic stations all over the world.

Consequently, seismic body and surface waves of the Hunga main explosion were recorded at seismic stations in Germany. The onset times of PKPbc phases determined at stations of the German Regional Seismic Network (GRSN) as well as corresponding slowness and azimuth calculated by array methods allowed an unambiguous assignment to the Hunga event and an epicenter localization deviating approximately 1 to 1.5 degrees from the volcano. Furthermore, at least one additional event is detected about 4 minutes after the main event.

To assign a seismic magnitude to the Hunga event, we analyzed the surface wave trains. The Ms magnitudes vary between 5.8 and 6.3 within the individual stations of the GRSN, with a mean value of 6.0.

The Tonga-Kermadec subduction zone is characterized by strong earthquake activity. This allows us to compare seismic recordings of the Hunga event with those of earthquakes from the same area with shallow focal depths and comparable magnitudes. It turns out that PKP phases of the Hunga eruption have significantly smaller amplitudes in the short-period range than for the compared earthquakes but similarly strong in the long-period range. We conclude that a long-period excitation is characteristic for the seismically relevant focal process of the Hunga event.

JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Wavefield analysis of volcanic tremor during the 2021 eruption of La Palma, Canary Islands, using multiple seismic arrays

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The 2021 Tajogaite eruption in La Palma, Canary Islands, was accompanied by strong volcanic tremor. In September 2021, during the first two weeks of eruption, we deployed two small-aperture seismic arrays. We chose two locations around Montaña Caldero and Llano del Jable, located about 4 km SE and 2 km NE of the eruption site. The arrays were composed of 1 three-component and 9 vertical-component short-period seismometers, sampled at 100 sps by a 12-channel data acquisition system. In each array, the receivers were spread with an aperture of about 400 m. Although they operated intermittently due to failures in the power supply related to ash fall, they provided long time series of multichannel seismic data that allow for the characterization of the syn-eruptive tremor. The analysis of the recorded wavefields reveals a persistent tremor source linked to the activity of the eruptive vents. The main component of the wavefield in the 1-3 Hz frequency band propagates with apparent slowness around 1 s/km, impinging on the arrays from directions of ~300 and 260ºN, respectively. These directions are slightly deviated from the active vents azimuths, a fact that we attribute to propagation effects produced by the topography and heterogeneous velocity structure. Subtle variations in the apparent slowness and propagation azimuths are investigated using the relative slowness estimate method, that allows for a precise determination of the apparent slowness vectors.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

IMAGMASEIS: a research project to image the magmatic plumbing system under Cumbre Vieja volcano using passive seismic methods

DOI: 10.57757/IUGG23-3591 - LINK

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We present a research project intended to investigate the structure of Cumbre Vieja volcano in La Palma, Canary Islands, after the September-December 2021 Tajogaite eruption. Starting in the summer of 2023, we will deploy a dense network of 35 broadband seismometers provided by GFZ and University of Granada, that will add up to the ~20 permanent stations already in operation by the Spanish National Geographic Institute (IGN) and the Volcanological Institute of Canary Islands (INVOLCAN). In this way, we expect to obtain a dense coverage of the whole island with inter-station distances of about 5 km. This broadband network will be in operation for a period of about a year. Additionally, we will perform a series of large-N experiments using 200 geophones (provided by GFZ). First we will deploy these instruments along linear profiles across the island, in N-S and E-W directions. In a second stage, we will move the geophones to a bidimensional grid configuration centered at the eruption site. We estimate that inter-station distances will be of ~0.5 km in both cases, and the recording periods will span around 4-5 months per configuration. The data obtained from these deployments will be used to perform a dense receiver function analysis and ambient noise tomography to improve the knowledge of the shallow velocity structure of the volcanic rift around the eruption area down to a depth of a few km and to image the magma sources in the crust and uppermost mantle.

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Lineament analysis based on satellite images as a tool for strain localization associated with seismic and volcanic activity

DOI: 10.57757/IUGG23-3764 - LINK

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The analysis of satellite images showed that the strain energy accumulation deep in the Earth's crust that precedes a strong earthquake can be detected by applying a lineament extraction technique. A lineament is a straight or a somewhat curved feature in a satellite image, which is possible to detect by a special processing of images based on directional filtering and/or Hough transform. We analyzed tens of earthquakes that took place in the Pacific coast of South America with a Richter scale magnitude over 4.5, using ASTER/TERRA and LANDSAT satellite images. All events were located in regions with small seasonal variations and limited vegetation to facilitate the tracking of features associated with the seismic activity only. The images were taken during the time interval of one year before and after an earthquake. It was found that the number and orientation of lineaments changes significantly one month before an earthquake approximately, and a few months later the system returns to its initial state. This effect increases with the earthquake magnitude. The application of the same technique to volcanoes showed that the behavior of lineaments associated to their seismic activity is opposite to that obtained previously for earthquakes. This discrepancy can be explained assuming that the main reason of earthquakes is compression and accumulation of strain in the Earth's crust due to subduction of tectonic plates, whereas in the case of volcanoes we deal with the inflation of a volcano edifice due to elevation of pressure and magma intrusion.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Characterization of the volcanic tremor during the 2021 Tajogaite eruption (La Palma, Canary Islands) through Distributed Acoustic Sensing

DOI: 10.57757/IUGG23-2766 - LINK

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In recent years the use of Distributed Acoustic Sensing (DAS) in seismology is gaining extensive usage in different applications. A High-Fidelity DAS system (HDAS) was deployed during the 2021 Tajogaite eruption on Cumbre Volcano (La Palma, Canary Islands), allowing the recording of most of the syn-eruptive and post-eruptive seismicity. The eruption lasted from Sep. 19^{th} until Dec. 13^{th} of 2021. The HDAS was installed on 19^{th} Oct. 2021 and is still operating.

The HDAS was installed around 10 km from the eruptive vent and was connected to a submarine fibre optic cable directed toward Tenerife Island. Since then, the HDAS has been recording seismic with a temporal sampling rate of 100 Hz and a spatial sampling rate of 10m for a total length of 30 (first phase) and 50 km using Raman Amplification (last period).

The HDAS recorded thousands of local earthquakes as well as regional and teleseismic events. It was revealed to be an excellent tool for volcanic monitoring, allowing a better location of deeper events which location was made difficult by the small aperture of the seismic network of La Palma.

The HDAS was also able to record the low-frequency (<1 Hz) component of the volcanic tremor up to a distance of tens of kilometres from the volcano. We show how, using array-like techniques, it is possible to identify and separate the volcanic tremor signals from the oceanic ambient noise. In this work, we demonstrate the effectiveness of using DAS as a real-time volcano monitoring tool.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Multiscale analysis of the background seismicity: Application to Campi Flegrei (Italy)

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This work is devoted to the analysis of the background seismic signal acquired in volcanic areas, specifically Campi Flegrei caldera (Italy), with the main aim to extract the statistical characteristics of the several transients and persistent signals occurring in that area. Indeed, any continuous seismic acquisition is not a trivial superposition of several seismic contributions coming from different internal or external sources. In particular, looking at the crisis of 2006 at Campi Flegrei, apart from the background hydrothermal noise, the meteo-marine contributions, and the anthropogenic noise, several Volcano-Tectonic and Long-Period events were recorded tracking the unrest phase. The identification of the statistical characteristics, in terms of high-order statistics and spectral contents, of any of these signals is crucial in the modeling and in the recognition. Here adopt the FIF analysis which is able to extract detailed information about the wavefield. We are able to identify the main characteristics of volcanic and non-volcanic signals, whose characteristics are general and not related to the investigated volcano. Moreover, this technique can well track any change in the dynamics of the caldera, revealing multi-scale patterns that are deeply changing when reaching the unrest phase. This provides a strong indication of the dynamic state of a volcano to be used in the monitoring processes.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Using machine learning for the classification of Seismic Signals at Vulcano, Italy

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A Vulcanian eruption is described as an eruptive style with strong explosive characteristics. The name derives from the island of Vulcano in Italy, the first place in which it was observed during the last eruptive activity between 1888 and 1890.
In this paper we analyze the seismicity recorded at Vulcano during a seismic unrest starting in September 2021 and still present as of November 2022. The distinctive feature of this seismicity is the presence of a variety of signals, most of which have a very long period (~0.5 s) signature. Low frequency content is interpreted as due to fluid involvement. Therefore, the high occurrence rate of VLP seismicity is a potential indication of pressure buildup within the volcanic system, and may herald phreatomagmatic activity (usually the first stage of a Vulcanian eruption), with serious consequences for inhabitants and tourists.Our analyses exploit machine learning procedures, with particular reference to pattern classification, at the aim of identifying varying classes of seismic events and trace their evolution over time. This classification can be useful for surveillance purposes contributing, along with other early warning methods, to reduce the devastating consequences of eruptions for people and property.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Stress transfer between volcanic dyke and seismic activity accompanying the 2021 Fagradalsfjall eruption, Iceland

DOI: 10.57757/IUGG23-4698 - LINK

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The 2021 Fagradalsfjall volcanic eruption in the Reykjanes Peninsula, Iceland, was preceded by a M_L 5.3 earthquake of 24 February 2021, which was followed by an intensive earthquake swarm lasting one month. Precise relocations show two hypocenter clusters in the depth range of 1-6 km. The swarm and later eruption occurred in the area which was the place of several swarms in the period of 2017-2020. We analyze the spatiotemporal characteristics of the activity, the Coulomb stress change caused by the ML 5.3 earthquake and by the magmatic dyke and the moment tensors of previous swarms to better understand the stress transfer between seismic and magmatic activity.

Our analysis shows a coincidence of several phenomena which could have contributed to driving the seismic and volcanic activity. The stress change analysis suggests that the forming magmatic dyke has increased the Coulomb stress on the M_L 5.3 earthquake fault. The following earthquake rupture resulted in unclamping of the fissure where the dyke formed and in Coulomb stress increase in the area of aftershocks and the following earthquake swarm. The WSW-ENE trending cluster of the 2021 and previous swarms show a stepover, forming an extension structure at the intersection with the dyke. And the moment tensors of the 2017 swarm events show that volumetric components vary along the cluster. Interestingly, the 2021 eruption occurred in the extension structure, suggesting that magma erupted at the place of crustal weakening.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Strain-rate field of Japan estimated from GNSS data using basis function expansion with ABIC

DOI: 10.57757/IUGG23-2680 - LINK

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Estimation of a strain-rate field from spatially discrete geodetic data has been a longstanding issue. On this problem, Okazaki et al. (2021) has recently developed a method based on basis function expansion with smoothness prior. In their method, the relative weight between observed data and the prior are objectively determined by Akaike's Bayesian information criterion (ABIC; Akaike, 1980; Yabuki and Matsu'ura, 1992); bi-cubic B-spline functions are used for basis functions, which makes inversion computation much faster (Nozue and Fukahata, 2022). By applying the method to GNSS data in Japan, strain-rate fields are estimated for three periods: 1997-1999, 2006-2009, and 2017-2020; the number of the used GNSS sites for each period is 880, 1337, and 1340. Except for deformation related with volcanic activities and large earthquakes, the obtained strain-rate fields are roughly stationary in time, while they show large variation in space. In order to interpret such spatially heterogeneous deformation, plate tectonics is considered to be inappropriate, because it basically postulates rigid motion for each plate. Instead, we propose a framework of inter-arc and intra-arc deformation, considering that Japanese Islands are composed of five island arcs (Kuril, northeast Japan, west Japan, Izu-Bonin, and Ryukyu). Using the framework, we can easily classify complicated deformation in Japan into the inter-arc deformation, such as the formation of the Hidaka Mountains, and the intra-arc deformation, such as the Niigata-Kobe tectonic zone.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Stress and strain on Mt Etna. A synopsis of 20 years of continuous monitoring of seismic and ground deformation data

DOI: 10.57757/IUGG23-0837 - LINK

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Continuous acquisition of high quality geophysical data allows developing a comprehensive geodynamical picture of Mt. Etna and the adjacent areas. We focus on seismic and ground deformation data recorded in the time span 2002 to 2021. Ground deformation measurements on the western flank of the volcano reveal a general trend of inflation, which is an expression of volcano doming and progressive magma accumulation.

The seismicity on Etna shows a rather heterogeneous picture. In general, hypocenter depths increase from SE towards NW. Besides, shallow events are frequent in the central part of the area. Focal mechanisms provide information about the forces acting in the seismic source and rupture orientation. We used unsupervised learning - Self Organizing Maps and K-means clustering - for the classification of 577 seismic moment tensors.

In the shallow levels normal faulting is frequent. The dispersion of strike direction of the axes for these events mirrors the complex stress field caused by magma dynamics in the shallower portion of the plumbing system. P- and T- axes of deeper events – orientated radially and concentric with respect to the summit area - indicate the existence of a pressure source in the central part of the volcano. The volcano related stress field interferes with the regional field, partly overriding it. The prevalence of the former becomes evident by comparing strain release for volumes inside the volcano edifice to those for adjacent volumes. It is five to ten times larger than in adjacent areas even for the deepest layers.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Changes in the seismic complexity prior to and during the 2014 Holuhraun eruption in Iceland

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Section 2.1: Physics of Earthquakes and Volcanoes, Potsdam, Germany

Changes in seismic complexity could reveal the dynamic changes inside a volcanic system prior to an eruption, which can be utilized to improve eruption forecasting. Permutation Entropy (PE) is a robust method to quantify the complexity of a time series, by calculating it directly using the amplitude. Examples of successful PE applications are eruptions forecasting at Strokkur Geyser, Iceland, the 1996 eruption of Gjálp, Iceland, and the eruptions of Shinmoedake volcano, Japan, in 2011, 2017, and 2018. While PE could show temporal changes prior to an eruption, these features are not always prominent. To improve this method, we calculated not only PE by using seismic amplitudes, but also Phase Permutation Entropy (PPE) by using seismic instantaneous phases. We calculated both PE and PPE for seismic station FLUR from January 2014 to December 2015, which covers the eruption period of Holuhraun in Iceland. During the unrest period, both PE and PPE show changes in entropy, but their patterns are not always the same. While PE shows a strong increase which marks the onset time of dyke propagation two weeks before the main eruption, it does not show a clear transition toward the main eruption. In contrast, PPE only shows a gradual change when the dyke started migrating. Jowever, it displays strong changes at the possible subglacial eruptions on 23 August, the small eruption on 29 August, and the main eruption on 31 August 2014. This proves the capability of PE and PPE to contribute to the framework of eruption forecasting.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Detection and characterization of seismic and acoustic tremor at volcanoes using machine learning

DOI: 10.57757/IUGG23-1040 - LINK

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Volcanic tremor is a semi-continuous seismic and/or acoustic signal that occurs at time scales ranging from seconds to years, with highly variable amplitudes and spectral features. Having a fast, robust, automated method to detect and characterize tremor in high temporal resolution would be beneficial to eruption forecasting and monitoring efforts, as well as to retrospectively building tremor catalogs for research purposes. As part of the NSF-funded PREEVENTS eruption forecasting project, we test and develop a pair of machine learning algorithms (one for seismic, one for acoustic) that can detect tremor in near-real time and classify it according to its spectral signature. First, we manually label tremor time windows on single station seismic and low-frequency acoustic (infrasound) spectrograms from the 2021-2022 eruption of Pavlof Volcano, Alaska, and train a convolutional neural network and random forest algorithm for both data types. We then use the trained models to classify seismic and infrasound data leading up to, during, and after the eruption, and compare temporal trends observed in our classifications alongside eruption chronologies compiled by the Alaska Volcano Observatory. We also implement a local network-wide weighting scheme to reduce false detections. Lastly, we assess the transferability of our models by applying them on unseen data recorded from past eruptions at Pavlof and other Alaska volcanoes. We envision that our machine learning models will aid tremor-related monitoring and research, and will advance our understanding of the relationship between tremor and subsurface volcanic processes by making consistent tremor catalogs more accessible.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Volcanic tremor related to the activity of Volcán de Colima during December 2014 to August 2015

DOI: 10.57757/IUGG23-4788 - LINK

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During July 10th and 11th, 2015, Volcán de Colima experienced the most intense volcanic eruption since its Sub-Plinian explosion that occurred in 1913. During this phase, pyroclastic density currents were generated, reaching up to 10.3 km south of the volcano. Starting in January 2015, there was a significant increase in the occurrence of tremor signals including harmonic, monochromatic, broad-spectrum, spasmodic and banded tremor, as well as tremor composed of LPs and tremor accompanying Vulcanian explosions. In this study, we quantified the different types of tremor observed and correlated their occurrence throughout the various eruptive phases presented within the period December 2014 to August 2015. We also characterized the evolution of these tremors, determining their fundamental frequencies, overtones, spectral range, amplitudes, and patterns in the frequency gliding. This allows for a better understanding of the changes presented in the precursory, eruptive and post-eruptive seismicity related to the constant activity of the volcano during the period under study. Finally, we evaluated possible models that could explain the generation of the tremor signals recorded during the analyzed period.

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JV04 - Posters - Volcano Seismology (IAVCEI, IASPEI)

Gradient measurements at volcanoes: Options, questions, pitfalls

DOI: 10.57757/IUGG23-2369 - LINK

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The recent advances in the hardware development of instruments that record gradients of the seismic wavefield made several novel measurement strategies at active volcanoes possible. Especially the recording of rotational motions is a prominent candidate to solve some of the problems that are eminent in volcano monitoring. Near field recordings of volcano-induced events often suffer from unaccounted effects of local tilt and unknown shallow velocity structure. In addition, if the station number is limited moment tensor inversions (MTI) are very often unconstrained. However, possible advantages of gradient measurements in these fields come also with a price: the wavefield gradient is very sensitive to local site conditions/heterogeneities.
To investigate the advantages and drawbacks of the combined recording of translational and rotational motion measurements (6C), we designed an experiment using six blueSeis-3A rotational motion sensors together with six TrilliumCompact seismometers at Stromboli volcano, Italy. In order to estimate the responses of different sites as well as to evaluate the performance of 6C recordings for location and moment tensor inversion, the stations were distributed along two rings at different height levels. Standard estimates of backazimuth and 1D-velocity profiles using 6C are performed. The results are compared to synthetic data which involve growing complexity of the modelled structure. The results of this tests confirm that local heterogeneities play a key role in the complexity of the recorded gradient wavefield. This complexity needs to be accounted for in order to be able to perform a MTI which should reduce the ambiguity using sparse seismic networks.

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FRIPON grazing fireball event detected by MOROI cameras

DOI: 10.57757/IUGG23-2613 - LINK

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[8]*CNRS – OSU Institut Pythéas, Service Informatique Pythéas, Marseille, France*
[9]*Aix Marseille Univ, Laboratory of Astrophysics of Marseille, Marseille, France*

In this work we present one of the most spectacular fireball events detected by the MOROI (Meteorite Orbits Reconstruction by Optical Imaging) (Nedelcu et al. 2018) part of the FRIPON (Fireball Recovery and Inter Planetary Observation Network) (Colas et al. 2020) all-sky camera network. The meteor was recorded on 3rd of November 2022 at 01:30:03 UT by cameras Bacau (ROBC01), Paulesti (ROPH01) and Obarsia Noua (ROOT01). The ablation phenomenon started at an altitude of 95 km above the sea level and the meteoroid fainted/ left the Earth's atmosphere at 90.6 km. The fireball event had a duration of 12.22 seconds. We determine the physical parameters of the meteoroid resulting from the luminous trajectory (Gritsevich 2008, 2009, Sansom et al. 2019, Boaca et al. 2022). We compute its mass, its velocity and determine the orbital elements using Meteor Toolkit (Dmitriev et al. 2015).

Boaca I., et al. (2022), ApJ, 936, 150.

Colas, F., et al. (2020), A&A, 644, A53.

Dmitriev, V., et al. (2015), PSS, 117, 223-235.

Gritsevich, M. I. (2008), DokPh, 53, 97.

Gritsevich, M. (2009), AdSpR, 44, 323.

Nedelcu, D. A., et al. (2018), RoAJ, 28, 57.

Sansom, E. K., et al. 2019, ApJ, 885, 115.

Acknowledgement.

The work of IB and AN was partially supported by a grant of the Ministry of National Education and Scientific Research, PNIII-P2-1214/25.10.2021, program no. 36SOL/2021. MG acknowledges the Academy of Finland project no. 325806 (PlanetS).

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Development of 2.05 um fiber lasers for CO2 DIAL lidar measuring martian CO2 and pressure

DOI: 10.57757/IUGG23-1022 - LINK

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Development of 2.05 um Fiber Lasers for CO2 DIAL lidar Measuring Martian CO2 and Pressure

A new concept of Martian differential absorption lidar (DIAL) operating in the 2050 nm CO2 absorption band for atmospheric CO2 and pressure observations has been proposed recently. Based on the concept, we are awarded to develop 2.05 um fiber lasers by the NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program. The laser is designed to be an all-fiber master oscillator and power amplifier (MOPA) system with laser output of ~3 mJ at a repetition frequency of 2 kHz. The primary master oscillator (PMO) is locked to the center of the selected CO2 absorption line (2050.428 nm). The frequency of a second MO (SMO) is locked to that of PMO. This SMO frequency is adjustable and switched between the online (2050.44156 nm) and offline (2050.50812 nm) wavelengths for demonstration. The online wavelength is optimally selected so that the CO2 absorption optical depth (AOD) is ~1.1 at 3 km and the measurement in the low Martian atmosphere has largest signal-to-noise ratio. The online wavelength can also be adjusted to a line slope location where AOD is larger to observe atmospheric pressure at higher altitudes. We will present more detail about this project and instrument development at the conference.

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JV06 - Posters - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Towards constraining Venus structure by means of atmospheric loading displacement response

DOI: 10.57757/IUGG23-2575 - LINK

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Surface mass loads produce a wide spectrum of deformation responses in planetary bodies that can be exploited to probe material properties in planetary interiors. In particular, the redistribution of fluid mass associated with Venus's atmospheric dynamics leads to periodic changes in the Venusian surface displacements and thus gravitational field. These periodic variations could potentially be detected by upcoming Venus missions, e.g., VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) and EnVision, which are expected to greatly improve our knowledge of Venus's gravity field.

By combining a state-of-the-art general circulation model of Venus's atmosphere with a novel approach to the solution of the quasi-static momentum equations in the coupled gravito-elastic problem, we explore the sensitivity of the atmospheric loading response to mantle structure. In addition, we investigate the effect of 3-D crustal and lithospheric variations on Venus's gravity field and the tidal and load Love numbers. Preliminary results suggest that an accurate estimation of the time-varying gravity field and surface displacements can provide important constraints on the interior structure of Venus through the measurement of the load Love numbers.

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JV06 - Posters - Geophysics of Solar System Planets (IAVCEI, IASPEI, IAG, IAGA)

Analysis of SL-Index and Hot Spot for extraction and quantification of knickzones over the Upper Alaknanda for prolonged river profile

DOI: 10.57757/IUGG23-3331 - LINK

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This work presents the SL-Index, one of the geomorphic indices which is extremely sensitive to variations in river gradient and serves as a useful tool for highlighting the disturbances along a river. In this study, we perform the different segmentation method with 3 fixed values of horizontal spacing (dL) = 1000 m, 1500 m, and 2000 m of the Middle Alaknanda Catchment. The SL-Index value was employed for the successive SL-Hot spot approach and further the SL-HCA map shows the spatial distribution of hot and cold spot using interpolation technique, that helps to select the zone of large landslides and principal knickzones. We generally concentrated on the positive or high anomaly since high values predicted over-steepened segments along the river channel. Then, to investigate the possibility of identifying the knickzones on a longitudinal stream profile, the analyses for this work were carried out using a 10 m resolution grid. The height and the elevation of knickpoints were analysed and it was observed that the largest portion of the knickpoints is situated in the upper part of the catchment or near river head. Further, to validate the SL-HCA approach, various knickpoints along the drainage network were assessed through the aerial imagery, validated with the detailed field survey. The findings of our result shows that the SL-index correlated well with knickpoints that controls the intensity of SL values is related to rock differential erosion, landslides, lithological variations, base-level changes, and the meandering course of the river.

Keywords: SL-Index, longitudinal river profile, knickzones, Alaknanda

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Keywords: SL-Index, longitudinal river profile, knickzones, Alaknanda

JV07 - Posters - The Architecture of the Lithosphere in Volcanic Regions (IAVCEI, IASPEI, IAGA, ILP)

Imaging of NE Japan volcanic arc by wide-band magnetotellurics

DOI: 10.57757/IUGG23-0555 - LINK

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Resistivity is a physical parameter sensitive to the existence and connectivity of the crustal fluids and melts. In this paper, we present a 3-D resistivity model covering an area of 50km x 50km in the central part of the NE Japan volcanic arc. We have compiled wide-band magnetotelluric data, which were collected over 30 years. We used full impedances and tippers of the 410 stations between 0.4 and 1,300s periods.

The final model shows the existence of a continuous low resistivity belt in the SSW-NNE direction along the volcanic arc in the deep crust (20 km to 30 km depth). On the forearc side, we also see a distribution of low resistivity anomalies, which imply fluid upwelling. These low resistivity anomalies in the deep crust correspond to strain-concentration areas along the volcanic arc and the forearc. The low resistivity zone along the volcanic arc locally shallows to a depth of 10 km, branching toward active quaternary volcanoes, such as Naruko volcano, Mt. Kurikoma, Onikobe caldera, and Takamatsu-dake. These swallow anomalies below the volcanoes imply magmatic melt and correlate well with the co-seismic subsidence zones due to "2011 off the Pacific coast of Tohoku earthquake" detected by InSAR.

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